PB86-115094

Test Firing Refuse-Derived Fuel in an Industrial Coal-Fired Boiler

Madison Dept. of Public Works, WI

Prepared for

Environmental Protection Agency
Cincinnati, OH

Sep 85

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-115094

EPA/600/2-85/113
September 1985

TEST FIRING REFUSE-DERIVED FUEL IN AN INDUSTRIAL COAL-FIRED BOILER

by

R. J. Vetter
City of Madison
Madison, Wisconsin 53709

M. L. Smith
M. L. Smith Environmental
Oak Brook, Illinois 60521

K. W. Ragland, R. K. Ham, R. P. Madding
University of Wisconsin
Madison, Wisconsin 53706

Grant No. R806328-01-3

Project Officer

Michael I. Black
Alternative Technologies Division
Hazardous Waste Engineering Research Laboratory
Cincinnati, Ohio 45268

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA/600/2-85/113	2.	3. RECIPIENT'S ACCESSION NO. PB86 115094 /AS
4. TITLE AND SUBTITLE TEST FIRING REFUSE-DERIVED FUEL IN AN INDUSTRIAL COAL-FIRED BOILER		5. REPORT DATE September 1985
		6. PERFORMING ORGANIZATION CODE --
7. AUTHOR(S) R.J. Vetter, M.L. Smith, K.W. Ragland, R.K. Ham, and R.P. Madding		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS City of Madison Dept. of Public Works, Div. of Engineering 210 Monona Avenue, Rm 115 Madison, WI 53709		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO. Grant No. R806328-01-3
12. SPONSORING AGENCY NAME AND ADDRESS Office of Research and Development U.S. Environmental Protection Agency Cincinnati, OH 45268		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA/600/12

15. SUPPLEMENTARY NOTES

Project Officer: Michael I. Black

16. ABSTRACT

The Research Program entitled, "Test Firing Refuse Derived Fuel in an Industrial Coal-Fired Boiler" evaluates the performance of an industrial boiler when co-firing coal and RDF. An optimum boiler operating load and RDF feed rate was determined for the boiler tested. Boiler efficiencies and stack emissions were also studied when co-firing RDF and coal. The economics of preparing and utilizing RDF in the boiler are evaluated. The operational characteristics of the RDF feed system and the reliability and practicability of receiving, storing, and firing RDF at an industrial operation are reported.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Release to public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 173
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local govenments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This project report evaluates a densified refuse-derived fuel with coal in a spreader-stoker fired boiler. The report examines the effect of the coal and densified refuse-derived fuel on plant operations, boiler efficiency, stack emissions and EP toxicity.

The information contained herein will be of interest to those designers or users who are contemplating or working with a system similar to the Ames system. Requests for further information regarding the production and utilization of refuse-derived fuel should be directed to the Thermal Destruction Branch, HWERL, Cincinnati.

David G. Stephan, Director
Hazardous Waste Engineering Research Laboratory

ABSTRACT

The Research Program entitled, "Test Firing Refuse Derived Fuel in an Industrial Coal-Fired Boiler" evaluates the performance of an industrial boiler when co-firing coal and RDF. An optimum boiler operating load and RDF feed rate was determined for the boiler tested. Boiler efficiencies and stack emissions were also studied when co-firing RDF and coal. The economics of preparing and utilizing RDF in the boiler are evaluated. The operational characteristics of the RDF feed system and the reliability and practicability of receiving, storing, and firing RDF at an industrial operation are reported.

A RDF Receiving and Feed Facility was designed and constructed to feed RDF to boiler no. 5, which had been modified to fire RDF, at the Oscar Mayer and Company Madison, Wisconsin plant. Boiler no. 5 is one of two base load coal fired boilers used by Oscar Mayer to produce steam for electrical generation and process purposes. Boiler no. 5 was co-fired with RDF and coal at various boiler loads and feed rates to determine an optimum operating condition. RDF from the Madison Area Resource Recovery Center was augered onto a slider belt conveyor and transported to the boiler house where it was mechanically split into six fuel streams and fed into the boiler.

Twenty-one tests were run from July 1980 to May 1981. Testing included evaluation of the coal and RDF; bottom, economizer, cyclone, and fly ash; underfire and overfire air; boiler efficiency; and gaseous emissions including SO_2, NO, HCl, and CO. Sixty-two trace elements in the fuel and ashes were measured.

The tests demonstrated that RDF could reliably be fed into an industrial boiler at feed rates up to 48%, on a heat input basis, while maintaining a steady steam load. In this boiler, which was modified to co-fire coal and RDF, the particulate emissions were not significantly increased when firing RDF. There was no negative physical impact on this boiler from the firing of RDF in combination with coal.

This report was submitted in fulfillment of Grant No. R806328-01-3 by the City of Madison, Wisconsin, Engineering Division under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of October 1, 1978 to November 15, 1981, and work was completed as of October 30, 1981.

CONTENTS

Disclaimer. ii
Foreword. iii
Abstract. iv
Figures x
Tables. xii
Acknowledgements. xiv

1. Conclusions and Recommendations. 1
2. Background 5
    National Municipal Solid Waste Management Practices 5
    Refuse Derived Fuel (RDF) Approach. 8
    Development of Refuse Derived Fuel Approach 9
3. The Madison, Wisconsin Resource Recovery Program 12
    Existing Program. 12
    Oscar Mayer and Company RDF Program 18
4. The Stoker-Fired Boiler Test Program 21
    Description of the Oscar Mayer and Company Boiler 22
        Boiler Design. 22
        Ash Handling System. 25
    Measurement and Analysis Methods. 26
        RDF Sampling and Analysis Methods. 26
        Coal Sampling and Analysis Methods 31
        Ash Sampling and Analysis Methods. 32
        Coal and RDF Feed Rate Measurements. 35
        Air Flow Measurements. 36
        Water Flow Measurements. 37
        Stack Sampling and Emission Analysis 37
        Boiler Efficiency. 42
    Test Results and Discussion 43
        RDF and Coal Properties and Feed Rates 43
        Ash Properties 58
        Boiler Operating Conditions. 72
        Boiler Efficiency Data 77
        Total Particulate Emissions. 84
        Gaseous Emissions. 89
        Trace and Minor Element Analyses of Fuels and Ash. 93
    General Observations - Boiler Operation and Performance 105
    Comparison of Test Results with other Test Data. 113
5. The Oscar Mayer RDF Feed System. 118
    Description of System Installed 118
        RDF Receiving and Storage. 118
        RDF Auger Feed Bin 118
        Material Conveying 120

5. The Oscar Mayer RDF Feed System . . . 118
  - Description of System Installed (con't). . . . 118
    - Flow Splitting and Feed into the Boiler . . . 122
    - RDF and Coal Combination Feeders. . . . 124
    - Overfire Air System . . . 124
  - Areas of Special Design Considerations and Alternatives Evaluated . . . 127
    - Litter and Dust Control . . . 127
    - System Controls . . . 129
    - RDF Feed Control and Continuity of Flow . . . 129
    - Conveying Between Buildings . . . 130
    - Flow Splitting at Furnace Wall . . . 130
    - Feed into Boiler. . . . 131
    - Equipment Interlocks . . . 132
    - Impact on Boiler Operations . . . 132
  - RDF Feed System Architectural and Design Considerations . . . 133
    - Site Location . . . 133
    - Traffic . . . 133
    - Facility Site Work . . . 135
    - Facility Structure . . . 135
    - Fire Protection. . . . 135
    - Facility Housekeeping and Dust Control . . . 135
    - Equipment Transition for Smooth Material Flow. . . . 137
    - Equipment Layout and Access for Maintenance. . . . 139

6. RDF Feed System Performance and Operation. . . . 140
  - Feed Characteristics of RDF General Observations . . . 140
    - Consistency . . . 140
    - Material Flow. . . . 141
    - Material Causing Jams . . . 141
    - Dust and Aesthetics . . . 142
    - Storage. . . . 142
  - RDF Feed System Operating Characteristics . . . 142
    - Outfeed. . . . 142
    - Feeder . . . 143
    - Material Conveying . . . 143
    - Flow Splitter. . . . 143
    - Feed into Boiler . . . 144

  - RDF Feed System Performance and Availability. . . . 145
    - Receiving and Outfeed System . . . 145
    - Material Conveying System. . . . 145
    - Flow Splitting System. . . . 145
    - Combination Feeder . . . 145

7. Economic Analysis . . . 147
  - 1980 Construction Costs . . . 147
    - RDF Receiving and Feed Facility. . . . 147
    - Boiler Modifications . . . 148
  - Projected Costs - Existing Facilities with Additions for Permanent Installation . . . 149
    - Projected Annual Capital Cost RDF Receiving and Feed System . . . 149
    - Projected Annual Operating Cost RDF Receiving and Feed System . . . 151

7. Economic Analysis (con't) 147
    The Oscar Mayer and Company RDF Market 152
    Fuel Value of RDF. 153

References 155
Appendices 158

A. Equations for Stack Sampling. 158

FIGURES

Number

Page

1 Madison Area Resource Recovery Center Plant Layout. 15
2 Madison Gas and Electric Company Boiler Cross-Section 17
3 Oscar Mayer Boiler No. 5 Cross-Section. 23
4 Average Size Distribution of Coal and Recommended Coal Size 46
5 Average Particle Size Distribution of Coal and RDF. 47
6 Average Proximate and Heating Value Analysis of Coal and RDF. 50
7 Average Ultimate Analysis of Coal and RDF 54
8 Average Particle Size Distribution of Bottom Ash. 61
9 Average Size Distribution of Economizer Ash 64
10 Average Size Distribution of Cyclone Ash. 66
11 Effect of RDF Heat Input on Combustible Content in Economizer Ash . . . 69
12 Effect of RDF Heat Input on Combustible Content in Cyclone Ash. 70
13 Effect of RDF Heat Input on Boiler Efficiency (HHV) 80
14 Effect of RDF Heat Input on Boiler Efficiency (LHV) 81
15 Efficiency (LHV) vs. Percent Excess Air 82
16 Efficiency (LHV) vs. Steam Load 83
17 Particulate Emissions vs. Heat Input from RDF 86
18 Oscar Mayer & Company RDF Receiving and Feed Facility 119
19 Slider Belt Conveyor Gravity Pulley 121
20 RDF Flow Splitting and Feed into the Boiler 123
21 RDF Sweeping and Distribution Air 125

FIGURES (continued)

Number Page

22 RDF and Coal Combination Feeder 126

23 Overfire Air System Boiler No. 5. 107

24 Proposed RDF Receiving and Feed Facility Additions. 150

TABLES

Number Page

1 Conversion Factors. 7

2 Oscar Mayer No. 5 Design Data 24

3 HCl, SO_2, and Trace Element Emissions 41

4 Average Particle Size Distribution of Coal and RDF. 45

5 Proximate Analysis and Higher Heating Value of Coal 48

6 Proximate Analysis and Higher Heating Value of RDF. 49

7 Ultimate Analysis of Coal 52

8 Ultimate Analysis of RDF. 53

9 Mineral Analysis of Fuel Ash. 56

10 Slagging and Fouling Criteria 57

11 Fusion Temperature of RDF and Coal Ash. 59

12 Average Particle Size Distribution of Bottom Ash. 60

13 Average Particle Size Distribution of Economizer Ash. 63

14 Average Particle Size Distribution of Cyclone Ash 65

15 Summary of Combustibles in the Ash. 67

16 Mineral Analysis of Bottom Ash and Slag 71

17 Total Sulfur and Chlorine in Ash (dry basis). 73

18 Air Flow Measurements Summary 75

19 Heat Losses and Boiler Efficiency 78

20 Summary of Particulate Emissions. 85

21 Cascade Impactor Measurements of Flyash 88

TABLES (continued)

Number Page

22 Summary of SO_2 Emissions. 90

23 Summary of HCL Emissions. 91

24 Summary of O_2, H_2O, Co, CO_2, and NO Concentration in Stack Gas 92

25 Elemental Analyses of Fuels and Ash 94

26 Trace Element Analyses of Coal (ppm). 97

27 Trace Element Analyses of RDF (ppm) 98

28 Individual Trace Element Analyses of Bottom Ash (ppm) 99

29 Individual Trace Element Analyses of Economizer Ash (ppm) 100

30 Individual Trace Element Analyses of Cyclone Ash (ppm). 101

31 Individual Trace Element Analyses of Fly Ash (ppm). 102

32 Trace Element Enrichment Factors for Ashes. 104

33 Comparison of Operating Conditions and Test Results with Other Locations. 114

34 Comparison of Operating Conditions and Test Results with Other Locations. 116

ACKNOWLEDGEMENTS

This report was prepared for the Environmental Protection Agency under Grant No. R806328-01-3. Mr. Michael Black, Alternate Technologies Division, Hazardous Waste Engineering Research Laboratory, Cincinnati, Ohio, served as EPA Project Officer for this grant.

The cooperation of the Oscar Mayer and Company is gratefully acknowledged. We are particularly indebted to: John E. Spohn, Madison Plant Manager, and Regional Vice President; James R. Stieve, Engineering Manager Madison Plant; Thomas Lisi, Power Plant Group Supervisor; John Blandford, Environmental Project Engineer; Robert Roemer, Utilities Project Engineer; William Selbo, Power Plant Supervisor; Donald Michaelis, Power Plant Supervisor; and Kenneth Wardell, Power Plant Supervisor.

The City of Madison was responsible for the overall grant coordination and administration including the final report preparation. The University of Wisconsin - Madison and the University of Wisconsin Extension were responsible for all phases of the industrial boiler testing, sampling, and analysis. M.L. Smith Environmental was a consultant to the project and assisted with the RDF feed system design, evaluation and final report preparation.

The principal authors of this report and individuals responsible for implementation of the program are: Robert Vetter, City of Madison Engineering, Division Project Director; M.L. Smith, M.L. Smith Environmental; Kenneth Ragland,

Professor of Mechanical Engineering; Robert Madding, Assistant Professor - Engineering Extension; Robert Ham, Professor of Civil and Environmental Engineering; Harold Olsen, Research Specialist and Svein Riibe, Graduate Research Assistant. Students assisting with data collection and analysis include: Philippe Maraval, Carlos Richer, Steven Johnson, Stephen Geisler, Ted Wilinski, Janet Krauze, and Jeff Horning.

Additional City of Madison personnel who assisted in the implementation and report preparation for this study were Kenneth Brunner, Madison Area Resource Recovery Plant Manager; Harry Chamberlain, Mechanical Repair Supervisor; Thaddeus Jagelski, Engineering Technician I; Mark Komurka, Drafting Technician II; and Marsha Peterson, Special Projects Section.

The research grant would not have been possible without the initial work of Gary L. Boley, formerly of the City of Madison's Engineering Division, in Project Development. His efforts are greatly appreciated.

The contributions of many other individuals, too numerous to mention, assisted in the completion of the project. Their contribution is appreciated and hereby acknowledged.

SECTION 1

CONCLUSIONS AND RECOMMENDATIONS

The research project was structured to:

1. Evaluate an industrial boiler's performance when co-firing coal and refuse-derived-fuel (RDF) at various boiler loads and feed rates to determine the optimum operating condition.
2. Evaluate air emissions and the performance of an existing mechanical air cleaning system when co-firing coal and RDF in an industrial boiler.
3. Analyze the economics of utilizing RDF in an industrial boiler.
4. Evaluate the operational characteristics of the RDF feed system and the reliability and practicability of receiving, storing and firing RDF at an industrial operation.

The conclusions drawn from the test work presented in this report are:

CONCLUSIONS

The project demonstrated that RDF prepared from municipal solid waste can be effectively burned with coal in a retrofitted industrial spreader-stoker boiler rated at 125,000 lb steam/hr (55,555 Kg/hr) equipped with a multi-cyclone particulate collector.

The best operating load, based on steam demand and boiler operation, was judged to be 90,000 lb steam/hr (40,000 kg/hr) with 33% of the steam load carried by RDF. This represents a coal feed rate of 3.5 T/hr (3,200 kg/hr) and an RDF feed rate of 3.8 T/hr (3,500 kg/hr).

The RDF produced for the test program had an average heating value of 5,785 Btu/lb (13,455 kJ/kg) with 21% moisture and 14% ash as received. The RDF has a nominal top size of 2 inches (5 cm), 90% less than 3/4 inch (1.9 cm), and mass mean size of 0.30 inches (0.76 cm).

The proximate analyses of coal and RDF indicated that RDF had higher volatile matter and lower fixed carbon contents than coal. The ultimate analyses showed that RDF was lower in carbon, nitrogen, and sulfur, and higher in moisture, hydrogen, chlorine, ash, and oxygen contents than coal. Coal had about twice as high a heating value as RDF on an as-fired basis. The main reason for the difference in heating values is the higher oxygen, moisture and ash contents of RDF.

Boiler efficiency decreased 1% for each 10% of heat load replaced by RDF. This decrease in efficiency was due primarily to additional moisture in the RDF and additional moisture from combustion of hydrogen in the RDF.

Particulate emissions ranged from 0.60 to 1.28 lb/million Btu (0.26 to 0.55 kg/million kJ). Fall 1980 tests co-firing RDF exhibited some excessive particulate emissions. Spring 1981 tests co-firing RDF showed no significant increase in particulate emissions as compared to the coal-only tests. It is believed that operating experience and lower RDF ash content contributed to the improvement in the later tests.

When co-firing RDF and Illinois coal at 90,000 lb steam/hr (40,000 kg/hr) with 33% of the heat load carried by the RDF, the sulfur dioxide emissions were reduced by half to 2.8 lb/million Btu (1.2 kg/million kJ), the hydrogen chloride emissions were increased 50% to 0.33 lb/million Btu (0.14 kg/million kJ), the carbon monoxide emissions were insignificant, and the nitric oxide emissions remained about the same at 0.4 lb/million Btu (0.17 kg/million kJ).

The trace element analyses of the fuels indicated that RDF was higher than coal in 36 out of 63 elements analyzed. Elements that were higher in concentration in RDF than in coal showed a general increase in all ashes with an increasing input of RDF. When burning RDF, trace metals were measured in the fly ash. Lead and zinc were each 2% of the total particulate emissions. The other trace metals were each one to three orders of magnitude lower.

The RDF receiving and feed system operated dependably providing a clean and constant flow of RDF to the boiler. The combination feeders utilized, distributed the RDF evenly throughout the boiler, maintaining a constant steam load.

The RDF storage and feed system at the Oscar Mayer Plant could be expanded to burn 12,500 to 15,000 tons per year of RDF while operating at 5 TPH, 10 to 12 hr. per day, 5 days per week. The fuel replacement rate would be approximately 40%. The projected operating costs to receive and burn 12,500 to 15,000 tons of RDF annually in the system described is $90,000 or $7.20 and $6.00 per ton respectively. The total September 1981 capital cost to install a permanent system as described would be $700,000. The cost to expand the test facility at Oscar Mayer to a permanent installation is estimated to be about $400,000. The economic analysis developed for this project indicates that the conditions to develop a market with Oscar Mayer appear favorable.

RECOMMENDATIONS

The co-firing of RDF and coal, in a retrofitted industrial spreader-stoker boiler should be further examined. It is recommended that additional co-firing of coal and RDF examine boiler performance while firing a larger RDF particle size in the range of 1 inch to 4 inches. RDF in this particle size range can be recovered from the residue stream at Madison's Energy Recovery Plant, further reducing the quantity of waste being landfilled.

Proper air distribution, in a boiler retrofitted to co-fire coal and RDF, is essential. Further testing is needed to optimize air distribution in a boiler which is co-firing coal and RDF in order to minimize excess air and reduce particulate emissions. Tests should include varying the ratio of underfire air to overfire air, and also the location, angle and penetration of the overfire air jet stream.

The short term co-firing of coal and RDF was successfully accomplished in Oscar Mayer's retrofitted industrial spreader-stoker boiler. No significant problems related to boiler operation or performance were evident during this test program. To further substantiate these preliminary findings, a long term coal and RDF co-fired test program, at optimum boiler load and RDF feed rates should be conducted to:

1. Insure boiler operator proficiency.
2. Establish a broad basis for evaluating emissions.
3. Investigate boiler fouling, corrosion, slagging, superheater degradation and additional maintenance problems.

The compostion and characteristics of particulate from a coal and RDF co-fired boiler varies from that of a straight coal fired unit. Therefore, the performance of various types of particulate control equipment need be studied under the co-fired condition.

Finally, the co-firing of coal and RDF in an industrial spreader-stoker boiler should be encouraged, both as a method of energy recovery and a means of reducing landfill space requirements.

SECTION 2

BACKGROUND

NATIONAL MUNICIPAL SOLID WASTE MANAGEMENT PRACTICES

A national effort has been under way, since 1960, to improve municipal solid waste management practices. This effort was prompted by such factors as unacceptable dumping practices, difficulty in siting new landfills, health considerations, vector problems, and wasteful practices.

Since the solid waste disposal act of 1965, several hundred million dollars has been spent by government and industry to study and demonstrate new concepts. The early work concentrated on improving and encouraging use of the more conventionally accepted methods of disposal such as sanitary landfill and modern incineration. Technologies used in other countries were also studied. These technologies included waste shredding, composting, and materials recovery.

Later work focused on the development of new concepts using American process industry technology. This work included the study of such technologies as fiber recovery, pyrolysis, and powdered, pulped, and fluffed fuels. The overall effort has produced noticeable improvements in the construction and management of sanitary landfills as well as improved operation and maintenance of incinerators and other waste disposal facilities.

It has also initiated development of a broad and much needed data base on such subjects as refuse characterization, material handling, performance of solid waste processing equipment, refuse processing residues and availability, reliability and safety of refuse processing schemes. Major cities from coast to coast are beginning to adopt the concept of resource recovery as a long term objective for solid waste disposal. The principal argument is that resource recovery can extend the life of existing landfills - this is one of the strongest arguments for recycling because of the difficulty in finding new landfill sites which are publicly acceptable, environmentally compatible and within an economic haul distance of the waste generators. Resource recovery also assures long term stabilization of disposal costs by making a fixed capital investment now, and establishing markets for recovered products which generate income and help hold down the rising costs of disposal.

Finally resource recovery represents an alternate energy source. Refuse can be converted into a marketable supplemental fuel with a heat value of 7000 to 8000 Btu/lb* on a dry weight basis. The RDF can be fired with coal and other primary fuels or fired as received in dedicated boilers to generate steam or power.

Depending on the form of fuel or energy produced and the local energy user market, each ton of raw refuse has the potential of generating $20 or more in income from sale as an energy product.

The cost of refuse haul and disposal has risen to $15 to $20 per ton at many regional landfills. Therefore, sufficient economic incentive exists to consider resource recovery as an option for improved municipal solid waste management.

Several North American cities recover energy from municipal solid waste including Madison, Wisconsin; Ames, Iowa; Saugus, Massachusetts; Chicago, Illinois; Nashville, Tennessee; Hamilton, Ontario; Niagara Falls, New York; Albany, New York;

---

*The data presented in this report is presented in English units. These units are consistent with industrial standards and have been utilized to simplify the use of the report. Factors for conversion to the International System of Units may be found in Table 1, Conversion Factors.

TABLE 1. Conversion Factors

Multiple	By	To Obtain
Btu	$1.055\ 056 \times 10^{3}$	Joule
Btu/lb	$2.326\ 000 \times 10^{3}$	Joule/Kilogram
Degree Fahrenheit	$t\ °C = (T°F - 32)/1.8$	Degree Celsius
Foot	$3.048\ 000 \times 10^{-1}$	Metre
$Foot^{2}$	$9.290\ 304 \times 10^{-2}$	Square Meters
$Foot^{3}$	$2.831\ 685 \times 10^{-2}$	Cubic Meters
Gallon (U.S. Liquid)	$3.785\ 412 \times 10^{-3}$	Cubic Meters
Inch	$2.540\ 000 \times 10^{-2}$	Metre
Ounce	$2.834\ 952 \times 10^{-2}$	Kilogram
Pound	$4.535\ 924 \times 10^{-1}$	Kilogram
Pound/Million Btu	$4.299\ 200 \times 10^{2}$	Kilogram/Million Joule
Lbf/in^{2} (psi)	$6.894\ 757 \times 10^{3}$	Pascal
Lb/ft^{3}	$1.601\ 846 \times 10^{1}$	Kilogram/Cubic Meters
Ton (short 2000 lb)	$9.071\ 847 \times 10^{2}$	Kilogram
$Yard^{3}$	$7.645\ 549 \times 10^{-1}$	Cubic Meters

Harrisburg, Pennsylvania; Baltimore, Maryland; Cockeysville, Maryland; and Salem, Virginia. A number of others are in various stages of construction, start-up, or modifications.

REFUSE DERIVED FUEL APPROACH

One of the types of energy which can be recovered from municipal solid waste is the heat value from a prepared refuse fuel.

Shredded RDF, with a partical size of 95% under 1-1/2 inch, has been suspension fired with coal in existing pulverized coal fired boilers in several locations including Madison, Wisconsin; Ames, Iowa; St. Louis, Missouri; Rochester, New York; Chicago, Illinois; and Milwaukee, Wisconsin.

In addition to size reduction, preparation of municipal solid waste for firing includes steps to remove metals and now combustible fines such as glass, sand, and dirt.

RDF has been fired in existing spreader-stoker boilers in Madison, Wisconsin; Ames, Iowa; Columbus, Ohio; and Pueblo, Colorado. Shredded RDF with a particle size of 95% under 4 inches has been fired with only ferrous metals removed in new dedicated spreader-stoker boilers in Hamilton, Ontario; and Albany, New York. A 4-inch RDF, with some classification to remove non-combustible fines in addition to metals, has been burned in new dedicated spreader-stoker type boilers in Buffalo, New York; Akron, Ohio; and Pueblo, Colorado.

Shredded RDF is frequently prepared off site and hauled in compacted form by 75-cubic yard enclosed transfer trailers to the point of use. At Chicago's Southwest plant, RDF has been transported by a 1,700 ft pipe from the City's processing plant. In some locations such as Hamilton, Ontario; Buffalo, New York and Akron, Ohio; new dedicated boilers designed to burn the RDF as a primary fuel are located at the site of fuel preparation.

Because of the inherent hazards and the difficulty of handling industrial and mixed commercial and industrial waste, the raw waste stream used to produce RDF is generally limited to municipal solid waste. This fraction includes largely residential waste and light commercial and institutional waste. Several forms of RDF have been tested. The most common is produced by simply shredding the waste, removing the ferrous, and screening or air classifying the balance of the waste stream.

Alternate forms of RDF have been produced using paper mill technology to produce a dewatered combustible pulp and chemical process technology to produce a powdered dry fuel. Neither of the latter approaches are currently in operation.

DEVELOPMENT OF THE REFUSE DERIVED FUEL APPROACH

Present RDF projects draw on the experience of early demonstration grants. During this period several important concepts were shown to be workable if properly applied. These concepts included, refuse shredding, magnetic separation, refuse screening, refuse air classification, and RDF transport, and storage.

Many approaches have been taken to prepare refuse fuel. These are outlined and discussed below.

Process Utilized	Location
1. Shred and air classify	City of St. Louis, Missouri Eastman Kodak, Rochester, New York Akron, Ohio Hooker Chemical, Buffalo, New York
2. Shred and magnetic separation	Hamilton, Ontario Columbus, Ohio Albany, New York
3. Shred, magnetic separation, fine shred, and air classify	Ames, Iowa (Original Plant)
4. Shred, air classify, fine shred, and disk screen	Americology, Milwaukee, Wisconsin
5. Rotary screen, fine shred, and air classify	New Orleans, Louisiana

(con't) Process Utilized	Location
6. Shred, magnetic separation, air classify, and fine shred	Southwest Plant, Chicago, Illinois
7. Shred, magnetic separation, disk screens, fine shred, and air classify	Ames, Iowa (After Modifications)
8. Coarse shred, magnetic separation, rotary screen, fine shred, and air classify	Madison, Wisconsin

As illustrated on the previous page, air classification has frequently been used in process plant design to separate combustibles from non-combustibles. The basis of this approach traces back to the simple use of air classification in the agricultural industry for such processes as separating grain from chaff. However, air classification of shredded refuse, which has a large variety of materials of differing shapes and densities, is a more difficult application of the technology. Most facilities have used fine shredding as a first step to achieve a uniformly sized waste product with a particle size of 90% under 3 inches, prior to downstream waste processing. This involves passing the waste through an 800 - 1250 Hp hammermill with 125 - 250 lb swinging hammers and sizing grates or equivalent shredder retention characteristics. This rugged approach to refuse shredding, ahead of air classification, attempts to produce a uniformly sized product, for air classification, from a hetergeneous refuse product which contains hard dense objects and bulky objects. Where refuse pulverizing has been used as a first step and air classification as the primary means of separation, the refuse fuels produced have retained most of the glass, sand and dirt, and other non-combustible fines. This method of processing has produced fuel products with ash contents causing high equipment maintenance. In some instances ash contents up to 35% have been experienced. High percentages of moisture have also been retained.

The high ash contents are caused by the entrainment of sand, dirt, glass, and small pieces of light gage metal, through fine shredding of the waste. Entrained with the mass of paper and other low density materials these ash characters are swept along with the refuse fuel. Much of the fine material will also "fly" in some air classifiers because of the high air velocities in the separation chambers.

Facilities producing high ash content fuels which attempt to pneumatically convey the material have generally experienced excessive wear in rotary air locks, and frequent jams in the pneumatic system because of heavy non-combustible fines dropping out of the air stream at pipe elbows.

As discussed earlier some refuse burning systems have been built to handle shredded refuse with minimum separation of non-combustibles. The Hamilton, Ontario, plant is essentially a municipal water wall incinerator designed to burn shredded refuse in a wind swept feed over a moving grate.

Some locations, Ames, Iowa; and Milwaukee, Wisconsin; added screens to the process in an attempt to remove glass and other inorganic fines. The screens in Milwaukee were added after the fine shredder while those in Ames were added ahead of the fine shredder. The City of Ames has experienced substantial improvement in refuse burning, pneumatic conveying and equipment wear.

Systems installed in New Orleans and Madison further extend the concept of screening refuse as a first step or prior to doing much work on the waste. Both locations use large rotary screens of the type used ahead of incinerators in many locations in Europe. The New Orleans plant screens raw waste while the Madison plant uses a low Hp, high capacity flail shredder to break bags and loosen and expose items in the waste before the waste is passed through a rotary screen. Both systems have consistantly produced a low ash fuel.

SECTION 3

THE MADISON, WISCONSIN RESOURCE RECOVERY PROGRAM

EXISTING PROGRAM

The City of Madison, Wisconsin has long been involved in the development of municipal solid waste management practices in the United States.

The City's Department of Public Works serves a population of 170,000 and collects approximately 60,000 tons of municipal solid waste annually [1]. The waste is collected by the Division of Streets and Sanitation and represents one-third of the total solid waste generated annually in the City of Madison. The Division of Streets and Sanitation collects from all single family residences, duplexes, four-unit apartment houses and some light commercial establishments. The remaining waste, generated from apartment complexes, larger commercial establishments and industry is collected by other governmental units, industry and private collection agencies.

Since September of 1967, the City has been processing municipal solid waste at the City's Olin Avenue site. Aided by a three and one-half year grant from the Department of Health, Education and Welfare, a demonstration project investigated the European concept of shredding municipal solid waste prior to landfilling, to improve the disposal characteristics of the waste. The project resulted in the acceptance of that practice and is being employed at facilities operated by both municipalities and private companies throughout the nation.

Madison's municipal solid waste processing system was expanded in 1971 to include a ferrous metal recovery system. Magnetic separation equipment was installed to recover the ferrous metal scrap from the shredded waste stream prior to landfilling. The recovered ferrous metal scrap, representing five percent of the total waste stream, was marketed to a local scrap dealer.

The development of Madison's present municipal solid waste processing system began in 1973. Faced with rapidly decreasing available landfill space, the City's then Director of Public Works, Edwin J. Duszynski, began exploring further utilization of Madison's municipal solid waste. He held talks with the president of Madison Gas & Electric Company (M.G. & E.), a local privately-owned utility, about the possibility of utilizing the combustible portion of the shredded municipal solid waste as a supplemental fuel to be co-fired with coal at M.G. & E.'s Blount Street Generating Station. The talks developed into a jointly financed feasibility study to evaluate the market and the practicality of this proposal. The study determined that the project was feasible and in January of 1977 the City and MG&E entered into a ten year agreement to fire prepared municipal solid waste in suspension with pulverized coal to produce steam for electrical power generation.

Based on the City's past experience in waste processing, a design team, comprised of the City of Madison's Division of Engineering, Division of Streets and a special consultant, began design of a 250 ton per day process plant to produce refuse-derived-fuel early in 1977. The design of the processing plant attempted to develop a processing system which would produce a high quality RDF product, maximize the utilization of the existing plant and personnel, and minimize the capital investment required. The design of the processing plant was finalized late in 1977, and in April of 1978 construction began.

Construction of the Madison Area Resource Recovery Center was completed in February of 1979, and in March of 1979 the first ton of refuse-derived-fuel was produced. A shakedown period followed, during which time the system was debugged and operating experience was gained. There were no major modifications required to achieve the desired end product. By June of 1979 the plant was processing at the design capacity of 250 T/day and by the fall of 1979 nearly 800 tons of RDF had been fired during the start-up stage at the utility.

The Madison Area Resource Recovery Center processes and disposes of approximately 250 tons of municipal solid waste daily on a single 50 T/hr process line. The 50 T/hr process line is comprised of four systems, including the primary shredder system, ferrous metal recovery system, separation system and secondary shredder system as shown in Figure 1.

The primary shredder is a flail type shredder designed to cut the refuse away from the head pulley of the feed conveyor (Conveyor No. 2) as it is pushed into the path of the primary hammers [2]. A minimal amount of work is done on the waste stream in the primary shredder. The waste is opened and exposed for magnetic separation and screening, which separates the combustible and noncombustible portions of the waste stream. The waste is discharged from the primary shredder at a nominal 10 inch particle size.

The coarsely shredded material is then conveyed (Conveyor No. 3) to the ferrous metal recovery system. The ferrous metal recovery system includes a single stage drum magnetic separator. The recovered ferrous metal is densified and conveyed (Conveyor No. 5) for air cleanup and discharged into an open top trailer for transport to a scrap market. The ferrous metal recovered represents 5% of the incoming raw municipal solid waste.

The balance of the coarsely shredded material is conveyed (Conveyor No. 4) to the separation system. The separation system incorporates a rotary screen designed to work most effectively with the coarsely shredded product from the primary shredder. The desirable combustibles are separated from the noncombustibles in the coarsely shredded waste stream. The noncombustible residue from

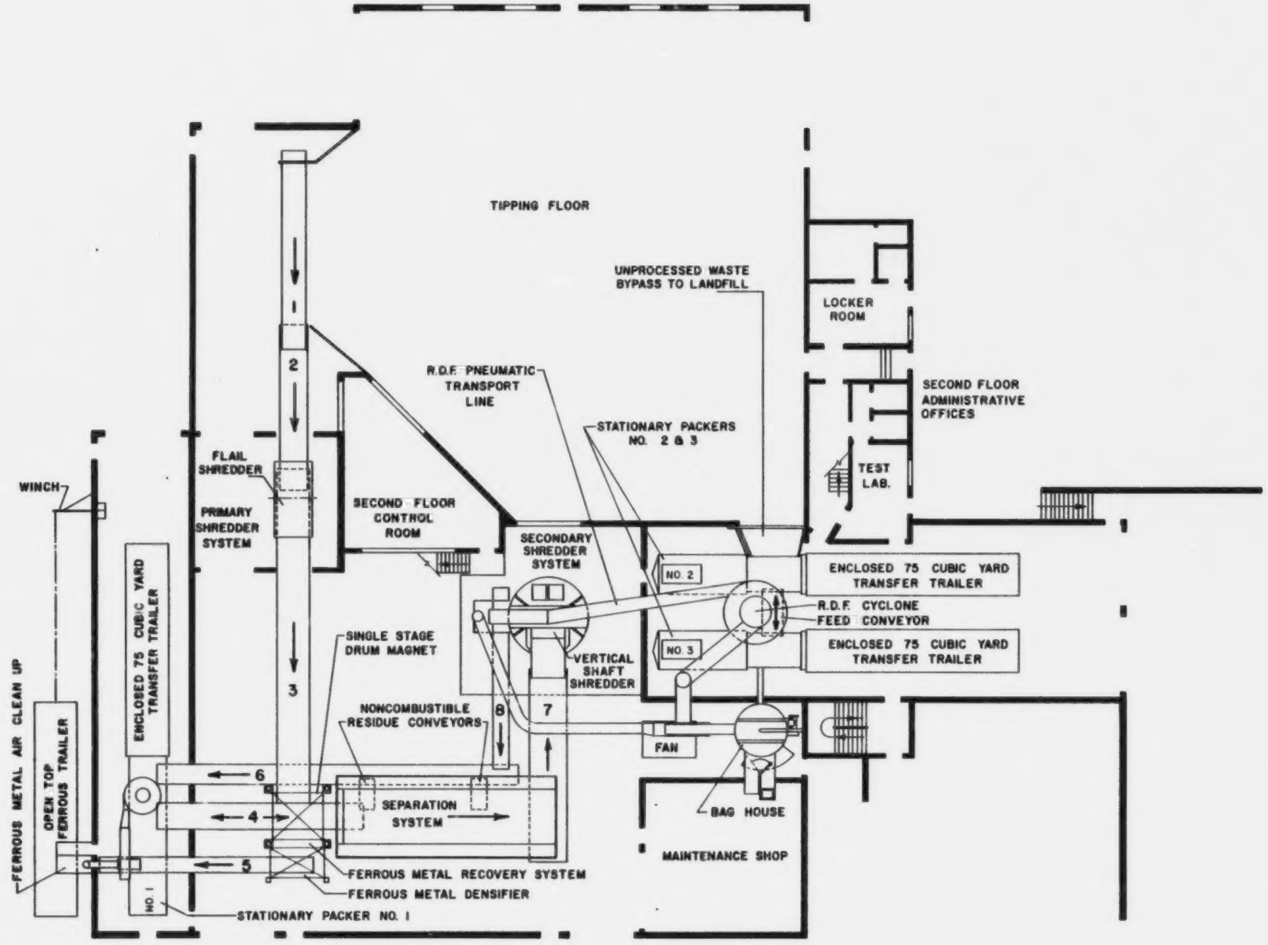
TIPPING FLOOR
UNPROCESSED WASTE BYPASS TO LANDFILL
LOCKER ROOM
SECOND FLOOR ADMINISTRATIVE OFFICES
TEST LAB.
R.D.F. PNEUMATIC TRANSPORT LINE
STATIONARY PACKERS NO. 2 & 3
FLAIL SHREDDER
PRIMARY SHREDDER SYSTEM
SECOND FLOOR CONTROL ROOM
SECONDARY SHREDDER SYSTEM
NO. 2
NO. 3
ENCLOSED 75 CUBIC YARD TRANSFER TRAILER
R.D.F. CYCLONE
FEED CONVEYOR
ENCLOSED 75 CUBIC YARD TRANSFER TRAILER
WINCH
ENCLOSED 75 CUBIC YARD TRANSFER TRAILER
SINGLE STAGE DRUM MAGNET
VERTICAL SHAFT SHREDDER
NONCOMBUSTIBLE RESIDUE CONVEYORS
FERROUS METAL AIR CLEAN UP
OPEN TOP FERROUS TRAILER
SEPARATION SYSTEM
FAN
BAG HOUSE
MAINTENANCE SHOP
FERROUS METAL RECOVERY SYSTEM
FERROUS METAL DENSIFIER
STATIONARY PACKER NO. 1
NO. 1
1
2
3
4
5
6
7
8

Figure 1. Madison Area Resource Recovery Center Plant Layout

the separation system is conveyed (Conveyor No. 6) to stationary packer No. 1 for transfer haul to the landfill. The desirable combustible waste, discharged from the separation system, is conveyed (Conveyor No. 7) to the secondary shredder system. The secondary shredder system includes a vertical shaft shredder designed to reduce the desirable combustibles to a fuel product whose particle size is 90 percent less than 3/4 inch. The finely shredded RDF is discharged directly into an air column for final separation by air, to remove any heavy undesirables from the final RDF product. The RDF is pneumatically transported through a cyclone and discharged onto a two-way conveyor (Conveyor No. 9) to feed two stationary packers (Stationary Packers Nos. 2 & 3) for loading into totally enclosed 75-cubic yard transfer trailers for transfer haul to M.G.&E.

The RDF is co-fired in suspension with pulverized coal at M.G.&E.'s Blount Street Generating Station in boilers nos. 8 & 9. These are 50 MW Babcock and Wilcox waterwall boilers with a design capacity of 425,000 lbs. steam/hr at 1,250 psig and 950° F. The RDF is injected into each boiler by means of two air-cooled injection nozzles located 26 ft above a dry ash pit. Drop grates were installed in the boiler throat above the dry ash pit to allow any RDF, not burned in suspension, to be completely combusted prior to discharge to the dry ash pit as shown in Figure 2.

The first full year of operation for the Madison Area Resource Recovery Center and the RDF receiving and feed facility at M.G.&E. ended December 31, 1980. Production records show that 52% of the raw municipal solid waste processed was recovered as refuse-derived-fuel. The RDF delivered to M.G.&E. has an average ash content of 12.7% on a wet weight basis, an average moisture content of 24.4% on a wet weight basis and an average heating value of 7,790 Btu/lb on a dry weight basis. The City of Madison received payment from M.G.&E. for the delivered RDF, at a rate equal to the cost of delivered coal on an equivalent heating value

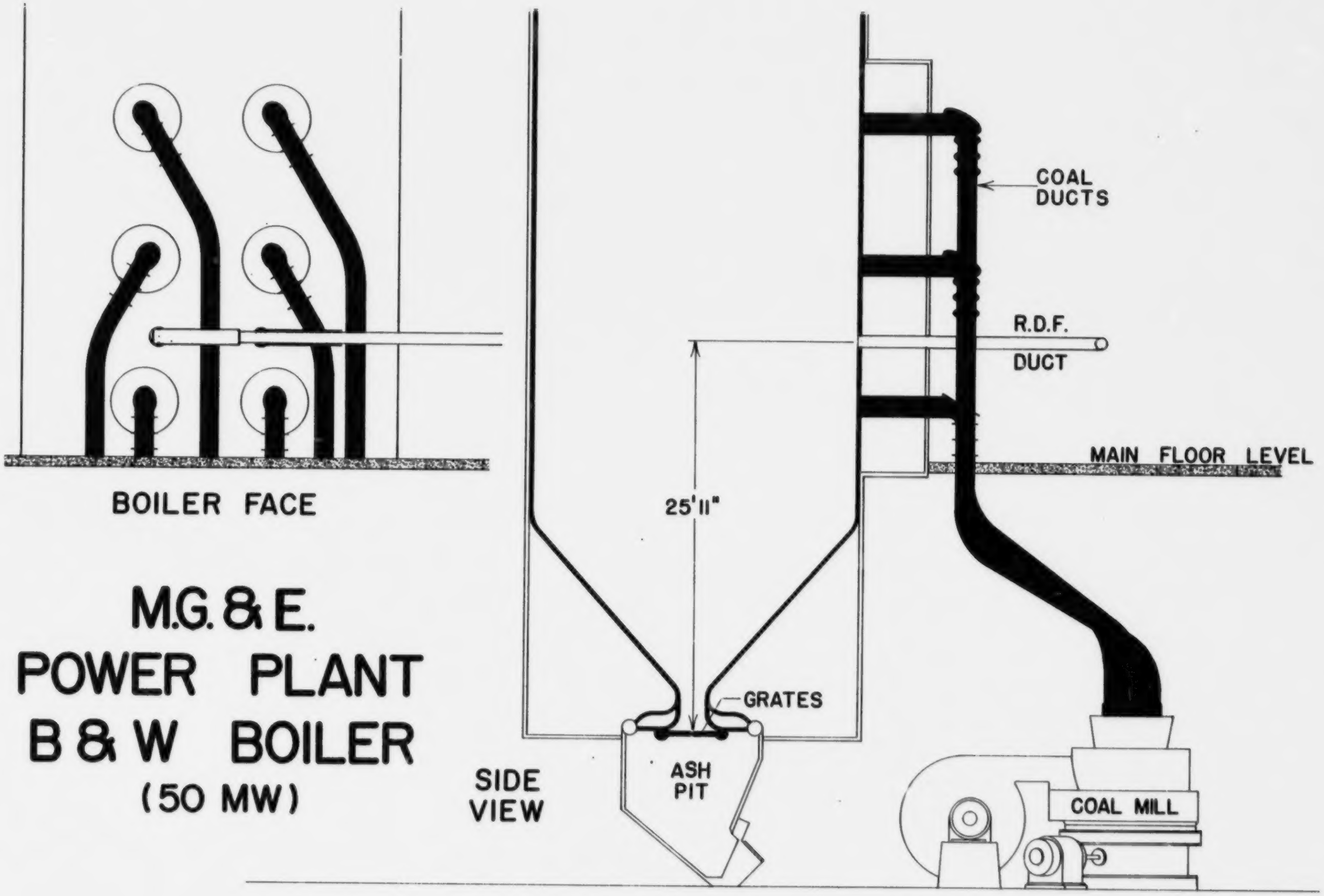
BOILER FACE
M.G.&E.
POWER PLANT
B&W BOILER
(50 MW)
SIDE
VIEW
COAL
DUCTS
R.D.F.
DUCT
MAIN FLOOR LEVEL
25'11"
GRATES
ASH
PIT
COAL MILL

Figure 2. Madison Gas and Electric Company Boiler Cross Section

basis. The value of the RDF for the second quarter of 1981 was $1.714/million Btu delivered. The availability of the Madison Area Resource Recovery Center for RDF processing in 1980 was 85% and the availability of the RDF receiving and feed facility for RDF firing in 1980 was 88%. Through June of 1981 both facilities have been available for processing and firing RDF more than 94% of the time.

OSCAR MAYER & COMPANY RDF PROJECT

The City of Madison submitted a detailed proposal in June of 1978 in response to the United States Environmental Protection Agency's request for proposal, No. CI-77-0226. The request for proposal was designed to further the development of waste-to-energy technologies and investigate the feasibility of using municipal solid waste as a supplemental fuel in an industrial boiler.

Approximately 12% of the electricity generated in the United States is generated in industrial boilers smaller than 200,000 lb steam/hr. These boilers are owned and operated by industrial concerns for in-plant and process use. More than 50% of the roughly 42,000 industrial boilers in the United States are coal fired boilers and the balance are either oil or gas - fired boilers [3]. While many of these boilers are package type boilers and not capable of co-firing RDF, the industrial market is nevertheless a potentially high user of RDF as a supplemental fuel source. Also, industrial boiler installations are not able to take advantage of highly favorable fuel price breaks that the utilities obtain, due to their high volume consumption.

Oscar Mayer & Company, a national meat processor whose corporate offices and largest meat packing plant are located in Madison, met all the criteria outlined in the request for proposal and had an appropriately sized industrial boiler available for testing. Oscar Mayer's Madison plant operations include a power plant for co-generation of process steam and electricity. Power Plant boiler no. 5, a Combustion Engineering Inc. (Wicks) 4-drum water tube type, with rated steam capacity of 125,000 lb steam/hr, was evaluated and determined to be suitable for co-firing RDF.

In the fall of 1978 the City of Madison in cooperation with Oscar Mayer was awarded an Environmental Protection Agency research grant to test fire RDF in the Oscar Mayer Boiler. Other project participants included the University of Wisconsin - Madison, and M.L. Smith Environmental.

The City's grant responsibilities included overall project management and coordination, detail design of the RDF receiving and feed facility, and supply of the RDF feed stock. Oscar Mayer's contribution to the grant included providing the boiler and personnel for operating the boiler and the RDF receiving and feed facility. M.L. Smith Environmental provided technical direction and staff assistance, including engineering evaluation of the boiler, assistance in the preparation of necessary documents for the boiler retrofit work, development of the RDF receiving and feed system, test program assistance, and final report preparation. The University of Wisconsin - Madison provided the equipment and personnel necessary for sampling, data collection, analysis and preparation of technical reports.

Following the award of the grant, an engineering evaluation of the boiler and the detailed design of the RDF receiving and feed facility began. By June 1979 the required boiler modifications were designed and an order was placed for the equipment to retrofit the boiler. This was followed by the completion of the design for the RDF receiving and feed facility and equipment. The building and equipment contracts were prepared and bids were accepted early in 1980.

The retrofitting of the boiler began in March of 1980 and was completed in May of 1980. The construction of the RDF receiving and feed facility and the installation of the RDF feed equipment began in April of 1980 and was completed by June 1980. Start-up and shakedown of the RDF system ran from June of 1980 to October of 1980. The first co-fired RDF and coal test run took place on October 16, 1980. Four co-fired test runs were made between October 16, 1980 and November 11, 1980, when testing was suspended because of inclement winter weather. RDF was fired on a daily basis over the winter of 1980-1981 to gain additional operating experience and formal testing was resumed on March 3, 1981. The RDF co-fired test program was completed in May of 1981 with the last test run on May 5, 1981.

The project evaluated the operational and emission performance of a coal fired industrial boiler when co-firing coal and refuse-derived-fuel at various boiler loads and RDF feed rates. The acceptance of co-firing RDF with coal in industrial boilers can result in the development of RDF markets for other municipalities throughout the United States.

More specifically, the sucessful co-firing of RDF in the Oscar Mayer boiler would result in the development of a second market for RDF in Madison of approximately 12,500 tons of RDF annually.

There are several social benefits which result from the development of a second RDF market in Madison. The most significant benefit would be the savings of an additional 40,600 cubic yards of landfill space annually. This benefit becomes very significant to the residents of Madison and Dane County, in which Madison is located, because the life of all available landfill space in the county extends only to September of 1983. A second social benefit is a reduction in the consumption of non-renewable resources, namely coal and natural gas. Finally, the development of a second RDF market at Oscar Mayer & Company provides an opportunity for the City of Madison and a private industry, important to Madison's well-being, to work cooperatively in the implementation and operation of a project which can be beneficial to both.

SECTION 4

THE STOKER-FIRED BOILER TEST PROGRAM

This section contains a description of the Oscar Mayer boiler, the measurements and analytical method used, and the boiler test results and discussion.

The boiler testing started July 9, 1980 and 12 runs were made up through November 11, 1980. After a break for winter weather, 9 tests were conducted between March 3, 1981 and May 5, 1981. Coal only tests were run in July, 1980, and one in April, 1980. All the RDF tests were made with a nominal 2 inch particle size except for the last run which had a nominal RDF size of 4 inches.

The test program was originally set up to run at 3 steam loads (75,000, 100,000, and 125,000 lb steam/hr) and 3 RDF replacement rates, based on steam load of 0, 20, and 50%. However, once the test program started, it became apparent that the boiler should not be run above 100,000 lb steam/hr in order to meet the Oscar Mayer load requirements and operational practice. Secondly, the boiler operators did not want to drop the coal portion of the boiler load below 45,000 lb steam/hr in case of sudden loss of RDF feed. Hence the boiler test program was run at steam loads of 75,000 and 100,000 lb steam/hr with RDF replacement rates of 0, 20, and 50% except that the 75,000 lb steam/hr at 50% could not be run.

After the series of exploratory tests were made the optimum operating point for this boiler when burning RDF was selected as 90,000 lb steam/hr with

33% of the steam load carried by RDF, or approximately equal feed rates of coal and RDF on a mass basis. This load best suited Oscar Mayer's steam demand and operating practices. Three test runs were made at this best operating condition. The actual conditions achieved on a given day varied depending on the boiler operators, the plant load requirements and availability of other boilers in the system. Some test conditions were repeated. Hence, altogether, 21 runs were made rather than the original 13 called for in the proposal.

In addition to the 21 test runs, the boiler was operated frequently throughout the period from July, 1980 through May, 1981, using various steam loads and RDF replacement rates in order to gain operating experience. In all, a total of approximately 600 tons of RDF were burned at the Oscar Mayer boiler during this period.

DESCRIPTION OF THE OSCAR MAYER AND COMPANY BOILER

The design of the boiler, as modified to burn RDF, and the ash handling system are described in this section.

Boiler Design

The boiler tested was the Oscar Mayer boiler no. 5 which is a Combustion Engineering (Wickes) water tube boiler rated at 125,000 lb steam/hr with a Detroit spreader-stoker. Superheated steam at 425 psi and 660°F is delivered. A schematic drawing of boiler no. 5 is shown in Figure 3 and the design characteristics are summarized in Table 2.

The boiler was installed in 1949. Gas burners were added in 1970. The overfire air system was modified and the RDF feed system added in 1980.

The boiler tubes are a typical water wall construction with tubes exposed to the radiant flame and with a refractory tile backing with insulation between the refractory tile and the outer steel casing. The tubes are 3-1/4 inches outer diameter, set 9 inches on center. Bent type boiler tubes extend from

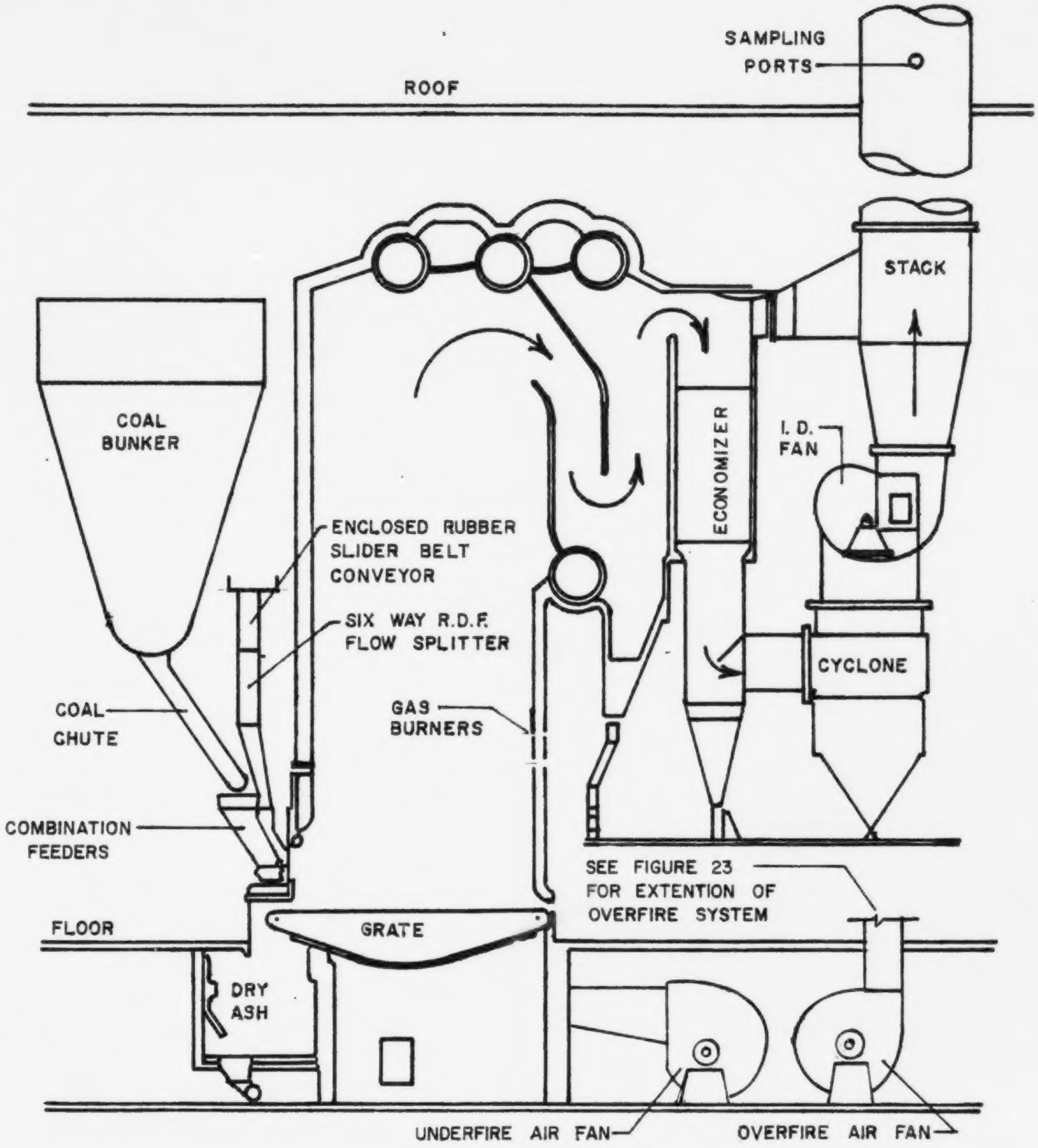
SAMPLING PORTS
ROOF
STACK
COAL BUNKER
I. D. FAN
ECONOMIZER
ENCLOSED RUBBER SLIDER BELT CONVEYOR
SIX WAY R.D.F. FLOW SPLITTER
CYCLONE
COAL CHUTE
GAS BURNERS
COMBINATION FEEDERS
SEE FIGURE 23 FOR EXTENTION OF OVERFIRE SYSTEM
FLOOR
GRATE
DRY ASH
UNDERFIRE AIR FAN
OVERFIRE AIR FAN

Figure 3. Oscar Mayer Boiler No. 5 Cross Section

TABLE 2. BOILER DESIGN DATA

Wickes Boiler

Design Steaming Capacity	125,000 lb/hr
Design Pressure	425 psi
Final Steam Temperature	660°F
Boiler Heating Surface	13,865 ft^2
Waterwall Heating Surface	2,540 ft^2
Economizer Heating Surface	8,100 ft^2
Furnace Volume	8,150 ft^3
Year Built	1949

Detroit Stoker

Number of feeders	6
Grate Type	Continuous Front Discharge
Grate Length (shaft to shaft)	18 ft-7 1/2 in.
Grate Width	17 ft-8 in.
Effective Grate Area	284 ft^2
Recommended Coal Sizing	1-1/4 in. to 10 mesh

Overfire Air

Upper Rear:	16 jets 1 in. diam. located 10 ft. above grate, 30 degrees below horizontal
Lower Rear:	16 jets 1 in. diam. located 18 inches above grate
Upper Front:	16 jets 1 in. diam., 10 ft. above grate, 35 degrees below horizontal
Lower Front:	20 jets 7/8 in. diam. 1 ft. above grate
Discussion:	The overfire air system is separate from the underfire air system, but 1/2 of overfire goes to RDF feed. Approximately 1/3 of underfire air goes to cool gas burner, and is introduced as overfire air
Soot Blowing:	Removed in 1951
Flyash Reinjection:	None
Air Preheater:	None
Cyclone Collector:	Western multicyclone

a lower mud drum to three upper steam drums, including a superheater section.

The coal stoker is a Detroit Stoker traveling grate spreader-stoker. The coal feed rate is controlled by means of adjustable weirs and by speed control of the rotary feeder. The grate has 1/4 inch diameter holes for the underfire air, and ash is continuously discharged off the front of the grate. The overfire air system is described in Table 2.

The boiler is equipped with a Western multicyclone collector with 9 inch diameter tubes. This cyclone collector was installed in 1949 and has a nominal collection efficiency of 92%. The I.D. fan is located 10 ft below the roof and 13 ft below the stack sampling ports in the 7.5 ft diameter steel stack.

Coal is delivered by rail to a conveyor which feeds to a hammer mill where it is reduced to 1-1/4 inch top size before entering the coal bunker. The RDF feed system is described in more detail in Section 5.

The Ash Handling System

The ash consists of bottom ash, economizer ash and cyclone ash. Bottom ash is collected on the traveling grate and continuously discharged to the ash pit below the grate. Once on each eight-hour shift, the ash doors are opened and the bottom ash is scraped into the pneumatic ash handling system for transport to the ash silo.

Economizer ash is removed from the flue gases in the economizer and the superheater section by gravitational forces and collected in four separate hoppers below the economizer. The ash is allowed to accumulate in these hoppers for about eight hours after which valves are opened and the ash is pulled by vacuum to the ash silo.

Cyclone ash is removed from the flue gases by the multicyclone collector and collected in two hoppers below this unit. After about eight hours accumulation of ash, a chute is opened and the ash is pneumatically transported to the ash silo.

The source of vacuum for the pneumatic conveyor system is a steam ejector. All the ash is transported to a common ash silo where it is sprayed with water for dust control. The ash is transported in trucks to landfills for disposal.

MEASUREMENT AND ANALYSIS METHODS

The measurement and analysis methods used for the RDF, coal, ash, air flow, water flow, stack sampling and boiler efficiency are described in this section.

RDF Sampling And Analysis Methods

The characterization procedures for the RDF used during this project were in part, developed or modified by Geissler [4]. According to the ASTM draft procedure for the collection and division of a gross sample of RDF [5], the number of sample increments required for a gross sample of RDF is given by:

$$N = 34 \times \frac{T}{1000}$$

where,

N = Number of sample increments per daily gross sample

T = Number of tons per day to be characterized

Four sample increments per gross daily sample is the recommended minimum.

With a maximum quantity of 25 tons burned during a test, the minimum of four sample increments would be sufficient. Geissler [4] found that a 45-minute sampling frequency was adequate to obtain a representative gross daily sample. He determined this on the basis of samples collected every 15 minutes throughout a day and analyzed for moisture, ash and higher heating value. A more convenient sampling frequency of 30 minutes was chosen for the tests.

Geissler further found that a sample mass of about 300 g is sufficient for moisture content determination of RDF.

The ASTM draft procedure for the Standard Method of Designating the size of RDF from its sieve analysis [5] states that an air dried sample of 2000 g should be used for sieve analysis.

Geissler, however, found that an air-dried sample of 1000 g would suffice. He could determine no significant difference between a 2000 g and a 1000 g air-dried sample.

RDF samples were collected at the Oscar Mayer facilities as the RDF was discharged from the augers onto the 24 inch wide rubber belt conveyor. Samples were obtained by opening a door at the end of the conveyor carrying the fuel to the boiler front. This sampling point was found to provide representative samples for this study, as described by Riibe [6]. The sampling at the Energy Recovery Plant could lead to too high moisture content data since the RDF frequently was stored overnight in the receiving building before firing, and evaporation did occur.

In accordance with the ASTM draft procedures for sampling the RDF [5], sample increments of about 1/2 ft^3 were taken from the cross-section of a free-falling stream and placed in 35 gallon plastic bags of 3 mil thickness. Sample increments were composited at the collection point to form the gross daily sample. Sample increments were taken every half hour. Gross daily samples ranged from 15 to 35 lb depending on the number of increments taken and the bulk density.

Preparation of a gross daily sample began with combining and mixing the contents of the two to three bags commonly collected. A coning and quartering procedure was then used to reduce the gross sample to four sub-samples of approximately 1500 g each. One of these sub-samples was air dried at 35°C in an open plastic bag for 72 hours. The sample was frequently mixed to insure even and complete drying. This sample was used for sieve analysis. A Gilson Testing Screen Model TS-2 was used with screen mesh sizes of 2 inch, 1-1/2 inch, 1 inch, 3/4 inch, 1/2 inch, 1/4 inch, #6, #12, #20, and #40. As specified in the ASTM draft procedure for sieve analysis of RDF [5], a 5-minute shaking time was used.

Another sub-sample was double bagged and stored at 4°C until the results of all the analyses were available. This sample could be used to check any suspicious results. The third sub-sample was discarded.

Two laboratory samples of 300 - 400 g were obtained by mixing and dividing the fourth 1500 g sub-sample. These two laboratory samples were placed in pre-weighed wire boxes lined with aluminum foil, weighed and dried to constant weight at 105°C in a mechanical draft oven for moisture content determination. The total moisture content is reported as the average of the duplicate determinations. The boxes were covered with cheese cloth to prevent any pieces of RDF from blowing out of the box.

One of the dried RDF samples was then randomly selected for grinding in a Wiley Mill. This sample was examined and non-grindables (aluminum) removed before grinding. The non-grindables were weighed and ashed at 730°C for correction of the analytical results. The remainder of the laboratory sample was then ground twice, using a 2 mm screen for the coarse grind and a 0.5 mm screen for the final grind to yield the analysis sample.

One 50 g sample of this fine ground material was separated by riffling and sent to Commercial Testing and Engineering in South Holland, Illinois for proximate, heating value, ultimate, mineral and ash fusion temperature analyses. The standard methods used for coal were used for these analyses. Additional portions of the fine ground material were used for trace element analyses.

The proximate analysis includes determination of the moisture content, ash content, volatile matter and fixed carbon according to ASTM D 3172, Standard Method for Proximate Analysis of Coal and Coke[7]. The proximate analysis provides useful information on the behavior of a solid fuel when it is heated; that is, how much of the fuel goes off as gas and tar vapors, called the volatile matter, and how much remains as fixed carbon. Moisture and ash contents are also of interest because these parameters indicate fuel inefficiencies and material handling requirements and are frequently included in fuel specifications.

The heating value is used as a measure of the potential heat energy available from a fuel. Commonly the higher heating value (HHV) is reported from laboratories. The Standard Test Method for Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter, ASTM D 2015 [7], was used for the HHV determinations.

The lower heating value (LHV) is obtained by subtracting 1030 Btu/lb of water, including both that are initially present as moisture and that formed by combustion, from the higher heating value. The lower heating value is of interest because it is a better basis for comparing fuels than the higher heating value since the water leaves the boiler in vapor form and is not condensed to liquid as in the higher heating value.

The ultimate analysis includes the determination of moisture, carbon, hydrogen, nitrogen, chlorine, sulfur, ash, and oxygen by difference according to ASTM D 3176, Standard Method for Ultimate Analysis of Coal and Coke [7]. The ultimate analysis is required for the computation of air requirements, weights of products of combustion and heat losses on boiler tests. Sulfur and nitrogen are of special interest from an air pollution point of view and chlorine, which forms hydrochloric acid upon combustion, is a factor in boiler corrosion.

The mineral analysis of a fuel ash, determined according to ASTM D 2795, Standard Method of Analysis of Coal and Coke Ash [7], provides an indication of the quality of the ash generated. The results can also be used along with other data, to evaluate potential slagging or fouling problems of the fuel.

Several parameters are used to provide information on expected slagging problems. Among them are the slagging factor and the T_{250} temperature, which will be defined and presented in Section 4, RDF and Coal Properties and Feed Rates. Four parameters are available for the evaluation of potential fouling problems: Alkalies as % Na_2O in coal (fuel), % Na_2O in ash, the fouling factor (defined and used in Section 4, RDF and Coal Properties and Feed Rates), and total % chlorine in coal fuel.

The fusion temperature of fuel ash, determined according to ASTM D 1857, Standard Test Method for Fusibility of Coal and Coke Ash [7], can be used to predict possible slagging and clinkering problems of the ash. There are no recognized, generally applicable limits on ash fusibility [8]; however, high ash fusion temperatures are beneficial for dry bottom furnaces and stokers. Generally, hemispheric reducing temperatures (HT) in excess of 2200°F are preferred [9].

Trace element analyses were conducted by the University of Wisconsin Nuclear Reactor Laboratory by means of Instrumental Neutron Activation Analysis. Calibration was done using National Bureau of Standards coal and fly ash (NBS 1632a and NBS 1633a, respectively).

Lead and Cadmium analyses were done by Atomic Absorption Spectrophotometry according to the Standard Test Method for Trace Elements in Coal and Coke Ash by Atomic Absorption, ASTM D 3683 [7], at the Sanitary Engineering Laboratory of the University of Wisconsin. Cadmium is not included in this method, however, ASTM states that it may be applicable. Comparison with NBS coal and fly ash was acceptable for lead (16.7 ppm and 80.8 ppm versus 12.4 ppm and 72.4 ppm given by NBS for coal and fly ash, respectively). The values are within the reproducibility interval of 9 ppm given in ASTM D 3683 [7]. For cadmium, however, the results did not compare favorably with the reported values. The concentrations obtained by method D 3683 were 0.9 and 4.8 ppm Cd compared to the reported concentrations of 0.17 and 1.0 ppm Cd for coal and fly ash, respectively. The reported concentrations of cadmium in samples analyzed by AA are probably too high.

The trace element analyses were primarily done to determine the concentrations of potentially hazardous elements. These elements will eventually be emitted to the atmosphere or be concentrated in the ash and may, if the ash is landfilled, cause groundwater pollution through leaching.

Coal Sampling And Analysis Methods

For Runs 1-12, coal samples were collected as the coal dropped off the conveyor into the coal bunker. The coal had by then already passed through a hammermill for size reduction. The coal samples were taken the day or night before the boiler test as the coal was loaded into the bunker by conveyor from a rail car for the next day's operation. From 15 to 18 sample increments of about 5.5 lb each were collected and composited in moisture tight plastic containers at the point of collection.

Starting with Run 13, coal was sampled from the hoppers immediately above the combination feeders. Two sample increments of about 5 lb each were collected randomly from the six hoppers every half hour during a test and composited in moisture tight plastic containers. The reasons for this change in sampling point of coal were the unreasonably long time (up to 8 hr) required to obtain a coal sample by the original method, and the often inconvenient times samples had to be taken.

Preparation of a gross daily sample began with thorough mixing, coning and quartering to reduce the gross sample to four sub-samples of 15 to 20 lb each. One sub-sample was double-bagged and stored at 4°C until the analytical results were available. This sample could be used later to check any suspicious results. A second sample was air dried by leaving it in an open plastic bag in a 35°C room for about 36 hr. This sample was used for sieve analysis, using the same equipment and sieve sizes as used for RDF. The only difference was the shaking time was held to 1 minute to prevent the coal from breaking into smaller pieces.

The third sub-sample was discarded. The fourth sub-sample was put in several preweighed wire boxes lined with aluminum foil and dried at 35°C. According to the Standard Method for Total Moisture in Coal, ASTM D 3302 [7], samples were left in the room until the weight loss was not more than 0.1 percent per hour. Percent air dry moisture was obtained by dividing loss in weight by total sample weight. The purpose of the air drying is to minimize moisture loss or gain during subsequent grinding.

The entire air dried sample was crushed to minus 2.38 mm (8 mesh) using a roller crusher. Two 500 g sub-samples were then obtained using a riffler for residual moisture determination according to the Standard Test Method for Total Moisture in Coal Reduced to No. 8 Top Sieve Size, ASTM D 2961 [7]. Those samples were dried to constant weight at 105°C.

Another sub-sample of 150 - 120 g was obtained by further splitting of the crushed sample. This sub-sample was ground to minus 74 mm (200 mesh) using a Norton Jar Mill (1-1/3 gal capacity) with cylindrical burundum grinding media.

Approximately 50 g of the fine ground coal was sent to Commercial Testing and Engineering for proximate, heating value, ultimate, mineral, and ash fusion temperature analyses. Additional samples of the fine ground coal were used for trace element analyses. These analyses were done for the same reasons, and the same procedures were used as were given for RDF in Section 4, RDF Sampling and Analysis Methods. Of special interest was the comparison of coal and RDF with respect to these various parameters.

Ash Sampling And Analysis Methods

Bottom ash samples were collected from the traveling grate at the point where the ash drops into the bottom ash pit. Samples were collected randomly through the six doors that open directly below the point where the ash falls off the grate.

Sample increments of approximately 1 kg each were collected every half hour throughout the duration of a test run and composited at the point of collection to produce gross daily samples ranging from 10 to 20 lb.

The gross daily sample was divided in half using a quartering procedure. A sieve analysis was performed on one of the sub-samples using the Gilson Testing Screen. The screens used were: 2 inch, 1-1/2 inch, 1 inch, 3/4 inch, 1/2 inch, 1/4 inch and #6. Shaking time was held to 20 seconds because the bottom ash separated readily and extensive shaking would cause breakage of the ash because it was very brittle.

The particle size of the bottom ash is an important parameter for the performance of the pneumatic ash conveyor system. A larger size bottom ash could cause the vacuum system to malfunction because the velocity of the carrier air would not be high enough to transport the largest particles.

The second sub-sample was crushed to pass an 8 mesh sieve using a roller crusher. The crushed sample was reduced in size using a riffler until a sample of about 150 g was obtained. A 500 g sample of the crushed material was extracted and stored for a possible later check of suspicious analytical results.

The crushed 150 g sample was ground to pass a 200 mesh screen using a Norton Jar Mill like the one used for coal grinding. The grinding took from three to five hours. A few grams of this fine ground material was used for determination of combustible matter in the ash according to the Standard Method for Ash in the Analysis Sample of Coal and Coke, ASTM D 3174 [7]. About 1 g of the analysis sample was burned to constant weight in a muffle furnace at 730°C. The average percent loss in weight on ignition of two to three samples was reported as combustible matter.

The combustible content of an ash is of importance for the boiler efficiency calculations. The combustible matter in the ash represents a direct loss in efficiency since it is a potential energy source that has not been used.

One analysis sample of about 50 g of the fine ground material was sent to Commercial Testing and Engineering for total sulfur and chlorine analyses and mineral analysis. Sulfur and chlorine analyses were done to determine the amount of these elements retained by the ash. Also of interest was the potential effect RDF would have on the concentration of sulfur and chlorine in the ashes. The analyses were started because a strong smell of reduced sulfur from the bottom ash was noticed while sampling this ash during the first co-fired test.

The mineral analysis of the bottom ash can give useful information on the ash with respect to clinkering and slagging problems. The mineral analysis of the bottom ash can be used to calculate several parameters that are useful for the ash characterization, as described in Section 4, RDF Sampling and Analysis Methods. However, because these parameters were developed for use on coal ash analysis, some of them cannot be directly applied to the bottom ash analysis. This is especially true of the slagging factor.

Trace element analyses of bottom ash were done using the same laboratories and procedures described for RDF in Section 4, RDF Sampling and Analysis Methods. Trace element analysis of the ash was done to determine any effect of the combined firing of RDF and coal on the concentration of various elements in the ash. Increased concentrations of potentially hazardous trace elements in the ash could lead to a higher risk of ground water contamination through leaching.

Economizer and cyclone ash were accumulated in enclosed hoppers directly below the respective units. Both ash hoppers were emptied at the beginning of each test run and ash was allowed to accumulate in the hoppers for the duration of a test run. Sample increments were taken through ports at the bottom of each hopper as the ash was pulled at the end of each run. These approximately equally spaced increments were composited to form two one-quart samples, one each of economizer and cyclone ash.

One 100 g sample and one 150 g sample were extracted from each of the gross ash samples using a riffler. The remainder of the ash was stored to be used for checks of any suspicious analytical results.

A sieve analysis was performed on the two ashes separately, using the 100 g samples. Standard 8-inch sieves were used. Screens ranging from No. 7 (2.83 mm) to No. 120 (0.125 mm) and from No. 18 (1.0 mm) to No. 230 (0.063 mm) were used. A Tyler Portable Sieve Shaker was used, and shaking time was 5 minutes. The particle sizes of these ashes were determined to see if co-firing RDF and coal had any effect on the size distributions.

The 150 g sub-samples were ground separately to minus 200 mesh using the same ballmill as used for bottom ash. A few grams of this fine ground material were used for determination of combustible matter in the ash. Procedures used were outlined for bottom ash. One sample each of economizer and cyclone ash of the fine ground material were sent periodically to Commercial Testing and Engineering for total sulfur and chlorine analyses. Trace element analyses were done as described previously.

Coal And RDF Feed Rate Measurements

The boilers at Oscar Mayer have no provisions for coal feed rate measurement. Since the fuel feed rate is an important factor in boiler efficiency calculations, a method for estimating the coal feed rate was developed based on measuring the level drop in the coal bunker over the duration of a test run. The coal in the bunker was manually leveled using rakes. Then elevations were measured from fixed points at 36 locations set by a grid pattern equally spaced over the bunker. From the estimated shape of the bunker and the coal bulk density, the coal feed rate was calculated.

In practice, however, these feed rate determinations were not used because their accuracy could not be verified and because the variability was large. Rather, the feed rates were estimated from the steam rate (Btu/hr), boiler efficiency based on lower heating value of fuels, fraction of heat input supplied by coal (from steam load chart) and lower heating value of coal (Btu/lb).

The feed rate of RDF was determined by stabilizing the boiler at a predetermined load with coal only and then suppling RDF until the desired steam production was reached without changing the coal feed rate. The boiler operators controlled the RDF feed rate by regulating the speed of the discharge augers. All changes in RDF discharge auger settings (speeds) were recorded on the boiler's steamload chart.

For each test run, transfer trailers transported a known amount of RDF to the receiving building at the Oscar Mayer & Company facilities. The total amount supplied was burned during each run. To obtain the average mass feed rate of RDF over the entire run, the total mass of RDF was divided by the feed time. To get the feed rate during the actual test (the period during which data was taken), the average feed rate was divided by the "total" average auger setting and multiplied by the average auger setting during the actual test. This calculation assumes a linear relationship between the auger setting (rpm) and the RDF discharge rate, which was shown to be true during auger calibration provided the feed rates are calculated on a dry basis [6].

For calculation purposes, the measured values for coal feed rates were not sufficiently accurate to give reasonable boiler efficiency results. To be consistent, it was decided to calculate RDF feed rates by the same method as for coal, i.e., on a steam rate basis.

Air Flow Measurements

Air flow rates were measured in the underfire air duct, the overfire air duct and the RDF distribution air duct. Kurz model 415T temperature compensated probes, consisting of a hot ribbon anemometer and temperature sensor were used. A two-wire, current mode transmitter at the end of each probe eliminated recalibration due to varying cable lengths. The signals from the probes were fed to

National Semiconductor ADC0816 single chip data acquisition system with an 8 bit A/D converter and 16-channel multiplexer, and then to a Commodore PET minicomputer with a 32-K byte memory. The software allowed on site selection of channels and sampling time increments. Output data was recorded on tape cassettes and also printed.

Underfire air test points were located 8 ft downstream from the fan and 1 ft upstream from the split to the auxiliary gas burners in a 9 ft by 3 ft duct. Overfire air test points were located 1.5 ft downstream from a tapered increaser and 1.5 ft upstream from the overfire damper in a 1.4 ft by 1.4 ft duct. RDF distribution air test points were locate 14 ft downstream from a right angle bend in a 13 inch by 13 inch duct. Sixteen equal area sampling points were used. (Thirty-two sampling points for the underfire air were shown to give essentially the same results as 16 points.) A center coefficient was established in each duct for a boiler test and used to determine a time average volume flow for the test. Wet bulb and dry bulb temperatures were measured at the fan inputs during each test.

Water And Steam Flow Measurements

Feed water flow rate was measured by an orifice at the inlet to the economizer and was recorded on the main control panel along with the water temperature at the inlet to the economizer. Steam flow rate was measured by a flow nozzle at the outlet from the steam header after the superheater was recorded on the main control panel along with the superheat temperature and pressure. The difference between the steam mass flow and the water mass flow varied between 5 and 10%, and was assumed to be due to boiler blow down, which was adjusted manually to maintain boiler water quality.

Stack Sampling And Emissions Analysis

Combustion products were sampled from two ports located 13 ft above the I.D. fan in the 7.5 ft diameter steel stack.

Three different sampling trains were used, one for particulate emissions and moisture, one for sulfur dioxide, hydrogen chloride and trace elements, and one for the oxygen, carbon dioxide, carbon monoxide and nitrogen oxide analyzers. Each of these three categories are discussed below.

Particulate Emissions --

The sampling procedure followed the EPA method 4 for moisture and EPA method 5 [10] for particulate loading. A 10 ft long by 3/8 inch inside diameter stainless steel probe, which was heated to 250° F, was used. The probe was connected to a Research Appliance Corporation source sampler which contained a glass cyclone collector and filter both heated in an oven, impingers to absorb moisture and finally the dry gas meter, pump and manometers. Three impingers were used; the first two were filled with 100 ml of distilled water plus 1 g sodium bicarbonate, to protect the pump from sulfuric acid, and the third contained silica gel. A fourth empty impinger was not used.

The sampling procedure was to make a 24 point traverse with 2 minutes at each point, collecting about 15 scf of stack gas, then recover the filter and move the set-up to the other port located 90 degrees around the stack. A 24-point traverse was made and the second filter recovered. The moisture catch was measured and the probe and cyclone wash (distilled water) was collected. A nylon brush on a wire was used when collecting the probe wash. A leak check was conducted before each traverse. A leak check after each traverse was not conducted for fear of damaging the filter cake and because the pressure drop across the filter was always small.

Usually the tests were run with a 3/8 inch sampling tip and a 65 mm filter diameter. The isokinetic condition was set by determining a constant K for each test run as shown in Appendix A. The meter temperature and barometric pressure were measured before the test. The stack gas moisture was estimated to be 6%.

The S pitot tube calibration factor was 0.81 as determined by laboratory tests. The orifice pressure was set for each traverse point by multiplying the pitot pressure by K. After the test was completed the velocity through the probe tip was compared to the stack velocity to insure that the velocity ratio was in the range 0.9 to 1.1. The equations for the moisture determination, molecular weight, velocities, excess air, average flow rate and particulate emissions are given in Appendix A.

Schleicher and Schuell glass fiber filters (grade 30) were used throughout, except that when trace elements were collected, Gelman spectro grade glass filters were used to insure low blank values. All filters were cut, desiccated for 24 hours, weighed and desiccated until the test. The filters were transported in a watch glass. After the test the filters were heated at 750°C for one hour and re-weighed. Trace elements on the filters were analyzed by neutron activation at the University of Wisconsin Nuclear Reactor Laboratory, except for lead and cadmium which were done by atomic absorption at the University of Wisconsin Sanitary Engineering Laboratory.

Size distribution of the fly ash was obtained with a six stage cascade impactor (Pollution Control System Corporation, Mark III D) with a BCURA cyclone mounted in front of the impactor. The cyclone was nominally 90% efficient for particles bigger than 2.5 microns and impactor stages ranged from 20 to 0.15 microns S and S glass fiber filters were used on each stage.

HCl, SO_2, and Trace Element Emissions--

One sampling train was used for these three measurements, but the impingers contents, flow rates and length of run were different. The probe was a 6 ft long by 3/8 inch diameter heated quartz probe. A glass wool plug in the end of the probe was used in each case. An impingement train with three to five Scientific Glass midget impingers in an ice bath was used. Temperatures were taken before and after the impingement train. A GII model 300 gas sampler containing a vacuum pump, a flow meter and a dry gas meter, and a heating system for the probe was used.

The sampling procedure for SO_2 followed EPA reference method 6 [10]. The sample was collected with a hydrogen peroxide solution and titrated with a barium perchlorate solution according to the method 6 procedure. The sampling procedure for HCl followed a modified EPA method 6 procedure [11,12] in which the sample was collected with a sodium hydroxide solution and titrated with a mercuric nitrate solution. Gaseous mercury was collected using a solution of ammonium persulfate and silver nitrate [13] and analyzed by neutron activation. Other trace elements are excepted to condense on the particulates and not be present in the gaseous emissions.

The impinger contents, flow rates and length of the sampling run are summarized in Table 3. For SO_2 the contents of the first, second, and third impingers and rinse were combined into one polyethlene bottom for analysis. For HCl the first impinger, second impinger, and probe plug and rinse were each kept in separate bottles. For mercury analysis the third and fourth impingers were combined for analysis. Details of sampling and analysis procedures have been recorded by Maraval [14].

CO_2, O_2, CO and NO Measurements--

Carbon dioxide was measured with a Thermoco Model P-12 thermal conductivity cell analyzer. No gas cleanup is needed for this instrument and a short stainless steel probe was used. The other three gases were sampled through a 4 ft long by 3/8 inch diameter stainless steel probe with a glass wool plug in the end. Moisture was removed by bubbling the sample through the water followed by drierite, a teflon coated vacuum pump, a dry gas meter and on to the instruments. The oxygen analyzer was a Teledyne Model 980 fuel cell instrument. The carbon monoxide was measured with a Sensors Incorporated series 5 infrared analyzer. The nitric oxide was measured with a Horiba Model P - 12 infrared analyzer. Zero air

TABLE 3. HCl, SO_2, and Trace Element Emissions

	HCl	SO_2	Trace Elements
Bubbler	---	15 ml 80% Isopropanol	---
1st Impinger	15 ml .01N NaOH	15 ml 3% H_2O_2	Empty
2nd Impinger	15 ml .01N NaOH	15 ml 3% H_2O_2	15 ml 30% H_2O_2
3rd Impinger	15 ml 30% H_2O_2	Empty	15 ml .2M $(NH_4)_2S_2O_8$ + .02M $AgNO_3$
4th Impinger	Silica Gel	Silica Gel	15 ml .2M $(NH_4)_2S_2O_8$ + .02M $AgNO_3$
5th Impinger	---	---	Silica Gel
Flow Rate (l/min)	2	1	0.7
Length of Run (min)	35	30	90
Volume Needed (ft^3)	3.0	1.0	1.0

and calibration gas were used to check the instrument calibrations before and during the tests.

Boiler Efficiency Method

The thermal efficiency of the boiler, n, was calculated using the ASME Power Test Code [15] by the indirect method according to the following relationship:

$$n = Q_{out}/(Q_{out} + Q_{loss})$$

where,

Q_{out} = heat output from boiler (Btu/hr)

Q_{loss} = heat loss due to dry flue gas + moisture in fuel + water from combustion of hydrogen + combustibles in ash + radiation loss (Btu/hr)

The heat output was determined from the steam flow rate and superheated steam temperature and pressure, an allowance was made for 5% blowdown of the feedwater to maintain water quality.

The heat loss due to dry gas emission was measured directly. The heat loss due to moisture in the stack gas was also measured directly. In order to split the inherent moisture loss from the moisture formed from hydrogen, the % RDF by weight in the fuel was determined as,

$$\% \text{ RDF} = 1/(1 + \text{lb coal/lb RDF})$$

where,

$$\text{lb coal/lb RDF} = \frac{\text{coal steam load}}{\text{coal LHV}} \times \frac{\text{RDF LHV}}{\text{RDF steam load}}$$

and,

LHV = lower heating value

The heat loss due to combustibles in the ash was determined from the measured combustibles in the ashes and assuming that the total ash consisted of 80% bottom ash, 6.7% economizer ash, 6.7% cyclone ash and 6.7% fly ash. The heating value of the combustibles in the ash was assumed to be 14,500 Btu/lb which is the heating value of carbon.

The radiation heat loss was assumed to be 0.67% of Q_{out}, which is based on the American Boiler Manufactures Association standard radiation loss chart[15] and an assumed thermal efficiency, but the variation was not considered to be significant.

A computer program was written to perform the boiler efficiency calculations.

TEST RESULTS AND DISCUSSION

In this section the test results and discussion will focus on the RDF and coal properties, the ash properties, the boiler operating conditions, the boiler efficiency determinations, the particulate and gaseous emissions data, and the trace element data. Summary data sheets for each run can be found in Appendices B and C.

RDF And Coal Properties and Feed Rates

The parameters used to characterize the fuels include: particle size, ultimate and proximate analysis including heating value, mineral analysis of ash, ash fusion temperatures and trace element concentrations. Trace element concentrations are discussed in a later section.

Particle Size of RDF And Coal--

The size specification given by Detroit Stoker Company for the boiler is 3/4 by 1-1/2 inch with no more than 10 percent passing a half inch round hole screen (roughly equivalent to a 0.37 inch square mesh screen). 3/4 by 1-1/2 inch (or approximately 1/2 by 1-1/4 inch square hole) means that 80 percent of the coal is retained between these screen sizes. The upper size is the smallest screen upon which less than five percent of a coal sample is retained and the lower is the largest screen through which less than 15 percent of the sample passes.

The coal burned during the boiler test did not conform to these specifications. From Table 4 and Figure 4 it is clear that the coal is much finer than specified. In Figure 4 ln(1/(1-y)) is plotted versus x (on log-log paper) where y is the cumulative fraction of material by weight less than size x. If the size distribution follows the Rosin-Rammler equation, $y = 1 - \exp(-x/x_o)^n$, the plot would give a straight line with slope n and $x = x_o$ when $\ln(1/1-y)) = 1$. Generally, the coal size distribution fitted this equation well. A size designation for the coal used during the boiler testing would be No. 12 by 1 inch on the average. Approximately 50 percent would pass a half inch round hole (0.37 inch square hole) screen.

The RDF consists of more fines than coal. As shown in Table 4 and Figure 5 the RDF gave 22.1 percent passing a No. 12 screen compared to 12.4 percent for coal, on the average. In addition to a general increase in ash production with RDF supplement firing, a relative increase in the economizer and cyclone ash production would be expected. However, since ash generation measurements could not be performed this cannot be verified.

Proximate Analyses of RDF and Coal--

Tables 5 and 6 give the results of the proximate analyses including higher heating values of the Illinois coal and RDF, respectively. According to ASTM D 388, Standard Specifications for Classifications of Coals by Rank 4, the coal used during the boiler testing is classified as high volatile A bituminous coal.

RDF is higher in moisture, ash and volatile matter, and lower in fixed carbon and heating value than coal. This is illustrated in the graphical representation of the average proximate analysis of coal and RDF in Figure 6. The higher volatile matter content of RDF indicates that RDF is a more quickly burning fuel than coal. Since the volatile matter is driven off as gases and tar vapors, a larger flame volume and more luminous flame would also be expected.

TABLE 4. AVERAGE PARTICLE SIZE DISTRIBUTION OF COAL AND RDF - PERCENT PASSING SCREEN

		COAL			RDF		
Screen	mm	Avg.	Std. dev.	C.V. %	Avg.	Std. dev.	C.V. %
2 in.	50.80	100.0	0	0	99.5	0.4	0.4
1 1/2 in.	38.10	99.6	0.9	0.9	98.7	0.7	0.7
1 in.	25.40	93.9	2.3	2.5	95.9	1.7	1.8
3/4 in.	19.05	82.9	4.6	5.6	90.5	2.5	2.8
1/2 in.	12.70	65.0	6.7	10.3	76.6	4.8	6.2
1/4 in.	6.35	37.3	9.2	24.6	42.4	9.8	23.1
#6	3.35	20.7	6.2	29.9	29.3	7.2	24.6
#12	1.70	12.4	4.3	35.1	22.1	5.0	22.7
#20	0.85	7.2	2.6	36.2	14.5	2.7	18.6
#40	0.42	4.1	1.4	34.0	9.9	2.3	23.1

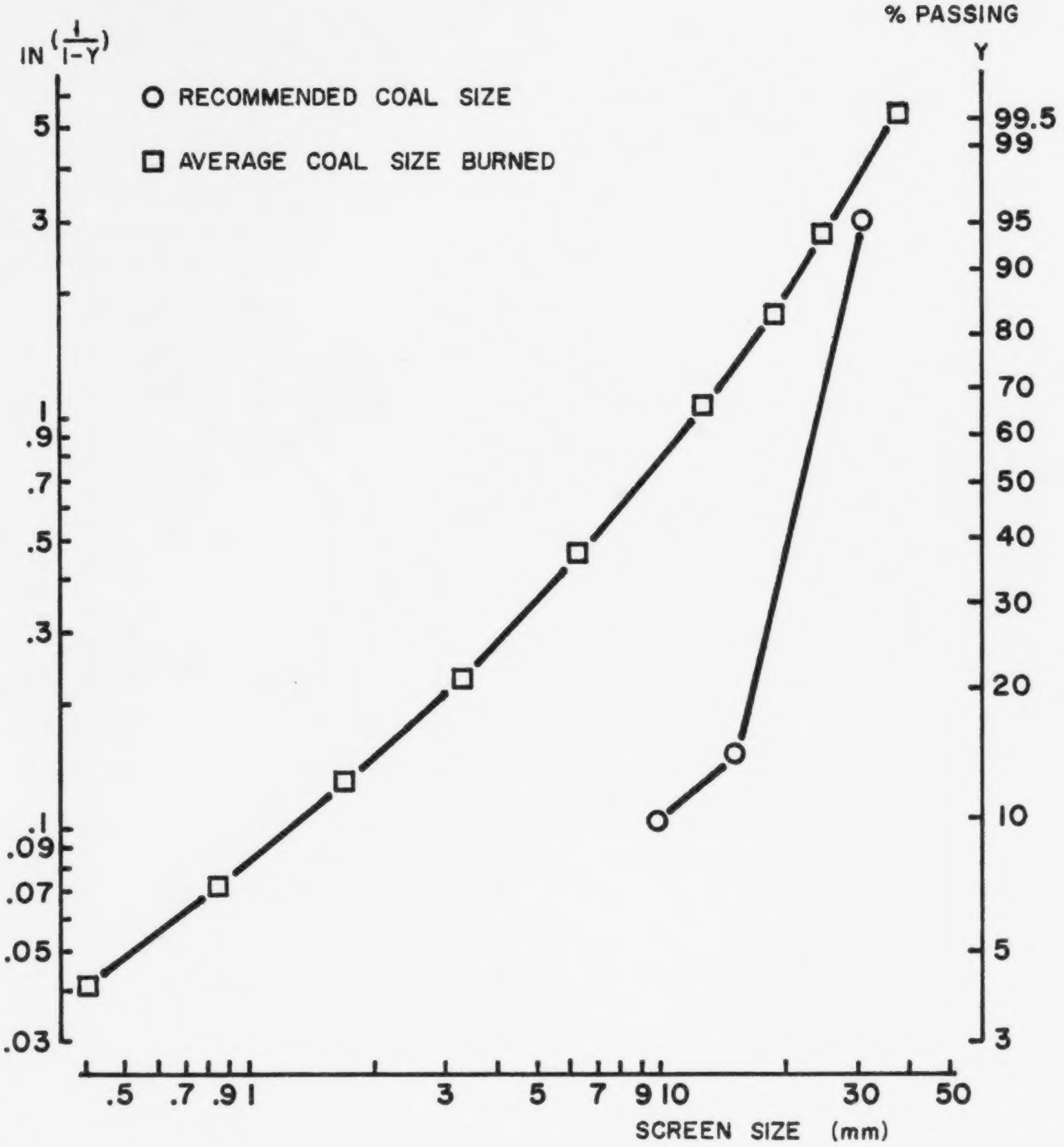

Figure 4. Average Size Distribution of Coal and Recommended Coal Size

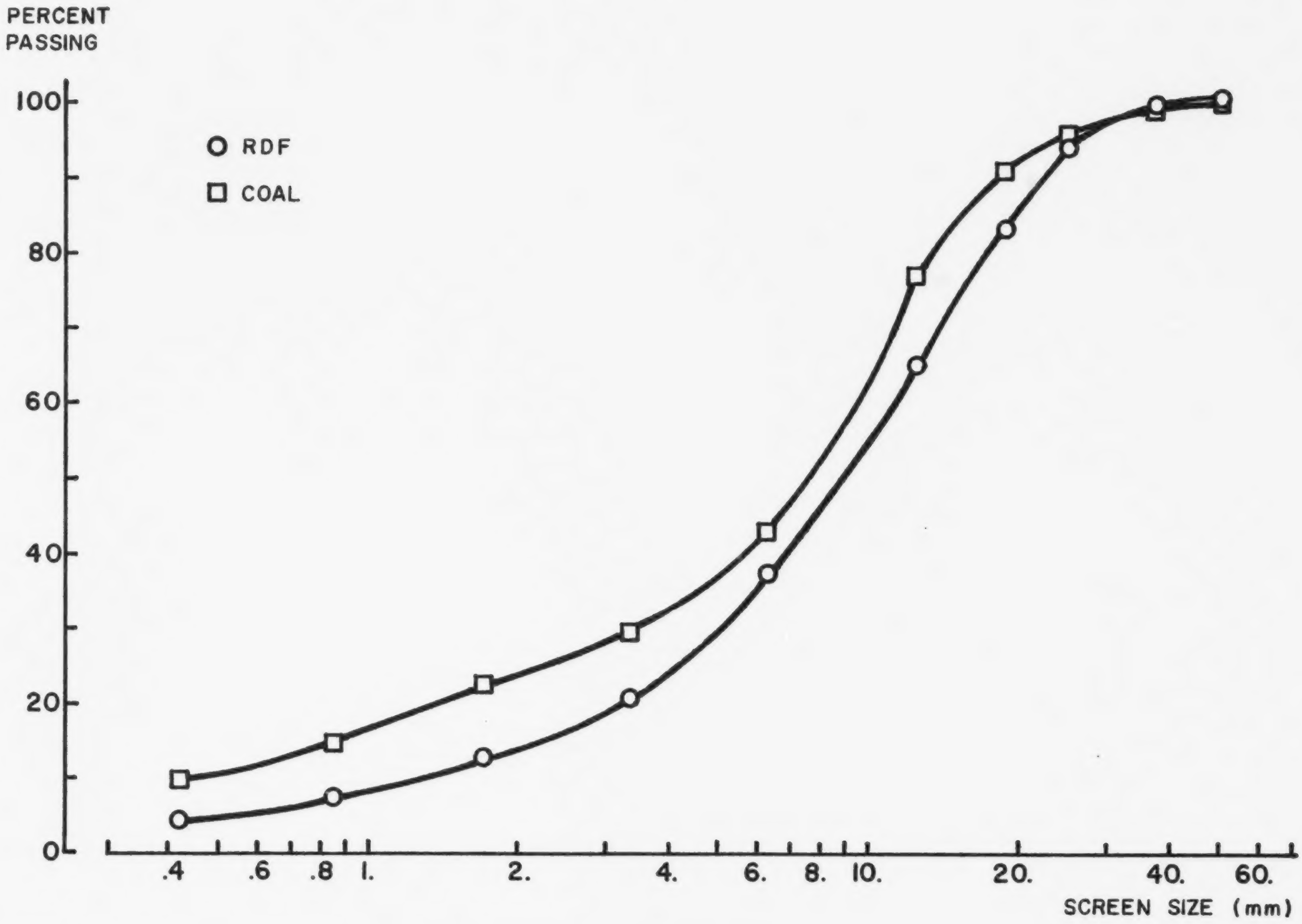

Figure 5. Average Particle Size Distributions of Coal and RDF

TABLE 5. PROXIMATE ANALYSIS AND HIGHER HEATING VALUE OF COAL

	% Moisture		% Ash		% Volatile Matter			% Fixed Carbon			Higher Heating Value		
Run #	ar	d	ar	d	ar	d	daf	ar	d	daf	ar	d	daf
3	4.51	4.72	10.51	11.01	38.81	40.64	45.67	46.17	48.35	54.33	12,552	13,145	14,771
6	7.26	7.83	7.91	8.53	34.18	36.86	40.30	50.65	54.61	59.70	12,882	13,826	15,115
9	5.22	5.51	9.87	10.41	35.60	37.56	41.92	49.31	52.03	58.08	12,604	13,298	14,483
10	5.09	5.36	9.44	9.95	36.98	38.96	43.26	48.49	51.09	56.74	12,659	13,338	14,812
11	6.64	7.11	7.91	8.47	34.82	37.30	40.75	50.63	54.23	59.25	12,614	13,511	14,761
12	5.19	5.47	11.77	12.41	37.37	39.42	45.01	45.62	48.12	54.94	12,310	12,984	14,824
13	8.54	9.34	9.11	9.96	34.01	37.19	41.30	48.34	52.85	58.70	12,233	13,375	14,855
14	6.07	6.46	8.98	9.56	34.03	36.23	40.06	50.92	54.21	59.94	12,572	13,384	14,799
15	5.67	6.01	8.54	9.05	35.78	37.93	41.70	50.01	53.02	58.30	12,770	13,538	14,885
16	5.40	5.71	8.96	9.47	34.94	36.93	40.79	50.71	53.60	59.21	12,734	13,461	14,869
17	5.92	6.29	11.49	12.19	35.32	37.54	42.75	47.29	50.27	57.25	12,217	12,986	14,789
18	7.39	7.98	10.24	11.06	34.59	37.35	41.99	47.78	51.59	58.01	12,147	13,116	14,747
19	5.64	5.98	9.87	10.46	36.41	38.59	43.29	48.08	50.95	57.16	12,552	13,302	14,923
20	8.60	9.41	8.21	8.98	35.96	39.34	43.22	47.24	51.68	56.78	12,100	13,239	14,545
21	8.73	9.56	9.45	10.35	36.64	39.05	43.56	46.18	50.60	56.44	11,857	12,991	14,491
Ave.	6.11	6.53	9.48	10.12	35.70	38.06	42.37	48.49	51.81	57.66	12,454	13,300	14,778
Std dv	1.36	1.56	1.17	1.19	1.37	1.21	1.66	1.81	2.00	1.65	291	235	167
C.V.%	22.2	23.9	12.4	11.8	3.8	3.2	3.9	3.7	3.9	2.9	2.3	1.8	1.1

ar = as received
d = dry
daf = dry ash free

TABLE 6. PROXIMATE ANALYSIS AND HIGHER HEATING VALUE OF RDF

Run #	% Moisture		% Ash		% Volatile Matter			% Fixed Carbon			Higher Heating Value		
	ar	d	ar	d	ar	d	daf	ar	d	daf	ar	d	daf
9	24.68	32.76	18.20	24.17	48.94	64.97	85.68	8.18	10.86	14.32	4872	6469	8531
10	23.21	30.23	15.02	19.56	52.30	68.11	84.67	9.47	12.33	15.33	4805	6257	7778
11	29.21	41.27	16.07	22.70	45.32	64.02	82.82	9.40	13.28	17.18	4670	6597	8534
12	24.34	32.16	15.30	20.22	50.94	67.33	84.39	9.42	12.45	15.61	5103	6744	8453
13	19.67	24.48	10.84	13.50	59.08	73.55	85.03	10.40	12.95	14.97	6414	7985	9231
14	16.28	19.45	11.28	13.47	62.56	74.73	86.36	9.88	11.80	13.64	6510	7776	8986
15	15.90	18.91	11.26	13.39	63.04	74.96	86.55	9.80	11.65	13.45	6348	7549	8716
16	14.55	17.03	14.18	16.60	62.11	72.69	87.15	9.15	10.71	12.84	6429	7524	9022
17	17.13	20.67	12.12	14.62	60.49	72.99	85.48	10.27	12.39	14.51	6525	7874	9222
18	22.95	29.79	11.84	15.37	55.48	72.01	85.09	9.72	12.62	14.91	5919	7682	9077
19	21.90	28.04	13.73	17.58	54.86	70.24	85.22	9.51	12.18	14.78	6036	7728	9376
21-I*	21.99	28.19	15.52	19.90	53.80	68.96	86.09	8.69	11.14	13.91	5489	7036	8784
21-II*	21.99	28.19	14.39	18.45	54.96	70.45	86.39	8.35	10.70	13.12	5788	7420	9099
Ave.	20.88	26.80	13.62	17.38	56.01	70.51	85.31	9.56	12.11	14.69	5785	7290	8811
Std dv	4.55	7.42	2.37	3.82	5.96	3.86	1.17	0.59	0.80	1.18	761	636	466
C.V. %	21.8	27.7	17.4	22.0	10.6	5.5	1.4	6.2	6.6	8.0	13.1	8.7	5.3

ar = as received
d = dry
daf = dry ash free

*not included in average

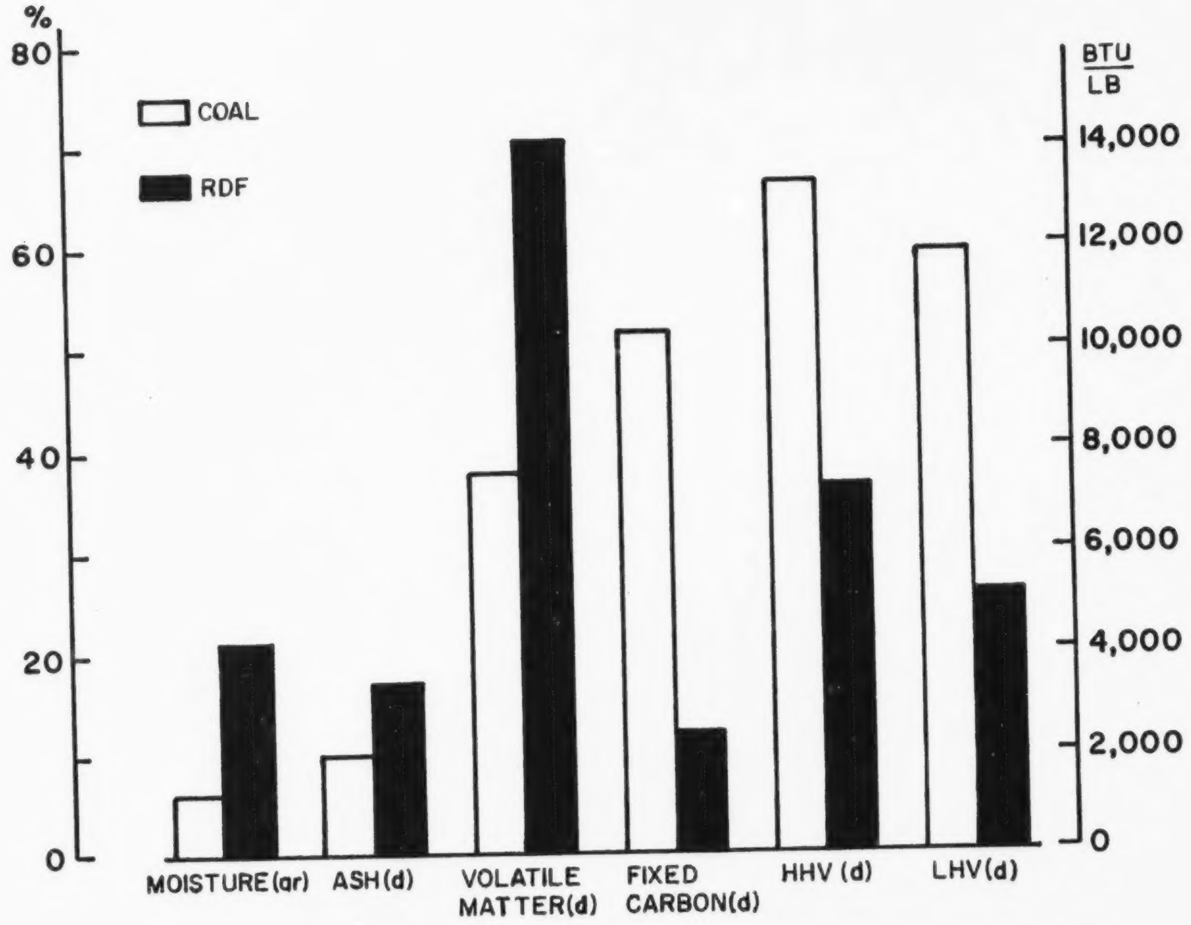

Figure 6. Average Proximate and Heating Value Analysis of Coal and RDF

These effects were observed during the test firing.

Heating Values--

The coal had an average as received higher heating value of 12,450 Btu/lb, a factor of 2.2 higher than the average RDF higher heating value of 5,790 Btu/lb. The variations in the heating value of RDF were much greater than for coal. The standard deviation in heating value for RDF was about 760 Btu/lb, while only 290 Btu/lb for coal. The larger variations for RDF are mostly due to larger variations in moisture and ash content, as may be observed by comparing the coefficients of variation for as received dry and dry ash free heating values of RDF in Table 6. The as received lower heating value for coal averaged 11,960 Btu/lb, while the RDF lower heating value averaged 5,150 Btu/lb.

Ultimate Analyses--

The ultimate analyses of coal and RDF presented in Tables 7 and 8, respectively, show that the RDF was considerably lower in carbon and sulfur, slightly higher in hydrogen, lower in nitrogen, higher in chlorine and much higher in oxygen content than coal. This is illustrated in Figure 7, where the average ultimate analyses of coal and RDF are presented.

The low carbon and high oxygen content of RDF is the main reason for the low heating value of this fuel. Oxygen in fuels is in combination with carbon or hydrogen and, therefore, represents a reduction in the potential heat energy of a fuel.

One advantageous feature of RDF is its relatively low sulfur content, which in this case was a factor of 16 lower than the coal on a weight basis or 7 on an equivalent heating value basis. This means that the sulfur input will be reduced 40 percent if 50 percent of the heat were to be supplied by RDF.

RDF contains about twice as much chlorine as coal on a weight basis, 0.31 percent versus 0.16 percent. On an equivalent heating value basis, RDF is a

TABLE 7. ULTIMATE ANALYSIS OF COAL

	% Moisture		% Carbon			% Hydrogen			% Nitrogen			% Chlorine			% Sulfur			% Ash		% Oxygen (diff.)		
	ar	d	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	ar	d	daf
3	4.51	4.72	-	-	-	-	-	-	-	-	-	0.17	0.18	0.20	4.17	4.37	4.91	10.51	11.01	-	-	-
6	7.26	7.83	69.67	75.12	82.13	5.00	5.39	5.89	1.34	1.44	1.57	0.15	0.16	0.17	2.76	2.98	3.26	7.91	8.53	5.92	6.38	6.97
9	5.22	5.51	68.70	72.48	80.90	4.78	5.04	5.63	1.45	1.53	1.71	0.17	0.18	0.20	3.81	4.02	4.49	9.87	10.41	6.01	6.34	7.08
10	5.09	5.36	69.06	72.76	80.80	4.87	5.13	5.70	1.26	1.33	1.48	0.17	0.18	0.20	3.51	3.70	4.11	9.44	9.95	6.60	6.95	7.72
11	6.64	7.11	69.91	74.88	81.81	4.57	4.89	5.34	1.49	1.60	1.75	0.14	0.15	0.16	2.83	3.03	3.31	7.91	8.47	6.52	6.98	7.63
12	5.19	5.47	67.11	70.78	80.22	4.78	5.04	5.71	1.27	1.34	1.52	0.16	0.17	0.19	4.10	4.32	4.90	11.77	12.41	5.63	5.94	6.73
13	8.54	9.34	-	-	-	-	-	-	-	-	-	-	-	-	2.73	2.98	3.31	9.11	9.96	-	-	-
14	6.07	6.46	69.49	73.98	81.80	4.72	5.02	5.55	1.18	1.26	1.39	0.17	0.18	0.20	2.86	3.05	3.37	8.98	9.56	6.53	6.95	7.68
15	5.67	6.01	70.35	74.58	82.00	4.91	5.21	5.73	1.35	1.43	1.57	0.16	0.17	0.19	2.77	2.94	3.23	8.54	9.05	6.24	6.62	7.28
16	5.40	5.71	70.39	74.41	82.19	4.91	5.19	5.73	1.43	1.51	1.67	0.17	0.18	0.20	2.87	3.03	3.35	8.96	9.47	5.87	6.21	6.86
17	5.92	6.29	67.04	71.26	81.15	4.76	5.06	5.76	1.65	1.75	1.99	0.19	0.20	0.23	3.85	4.09	4.66	11.47	12.19	5.13	5.45	6.21
18	7.39	7.98	67.01	72.36	81.36	4.56	4.92	5.53	1.51	1.63	1.83	0.17	0.18	0.20	3.34	3.61	4.06	10.24	11.06	5.78	6.24	7.02
19	5.64	5.98	68.90	73.02	81.55	4.84	5.13	5.73	1.62	1.72	1.92	0.19	0.20	0.22	3.35	3.55	3.96	9.87	10.46	5.59	5.92	6.61
20	8.60	9.41	66.66	72.93	80.13	4.62	5.05	5.55	0.99	1.08	1.19	0.05	0.06	0.07	3.04	3.33	3.66	8.21	8.98	7.83	8.57	9.42
21	8.73	9.56	65.59	71.86	80.15	4.57	5.01	5.59	1.27	1.39	1.55	0.08	0.09	0.10	3.38	3.70	4.13	9.45	10.35	6.94	7.60	8.48
Ave.	6.11	6.53	68.45	73.10	81.25	4.76	5.08	5.65	1.37	1.46	1.63	0.15	0.15	0.18	3.29	3.51	3.91	9.48	10.12	6.20	6.63	7.36
Std dv	1.36	1.56	1.58	1.40	0.75	0.15	0.13	0.14	0.18	0.19	0.22	0.04	0.04	0.04	0.51	0.51	0.61	1.17	1.19	0.70	0.81	0.85
C.V. %	22.2	23.9	2.3	1.9	0.9	3.1	2.6	2.5	13.3	12.9	13.5	26.1	24.5	24.6	15.4	14.6	15.7	12.4	11.8	11.2	12.2	11.6

ar = as received
d = dry
daf = dry ash free

TABLE 8. ULTIMATE ANALYSIS OF RDF

	% Moisture		% Carbon			% Hydrogen			% Nitrogen			% Chlorine			% Sulfur			% Ash		% Oxygen (diff.)		
Run #	ar	d	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	daf	ar	d	ar	d	daf
9	24.68	32.76	29.33	38.94	51.35	3.84	5.10	6.73	0.45	0.60	0.79	0.31	0.41	0.54	0.26	0.35	0.46	18.20	24.17	22.92	30.43	40.13
10	23.21	30.23	30.69	39.97	49.69	4.09	5.32	6.61	0.42	0.55	0.68	0.20	0.26	0.32	0.18	0.24	0.30	15.02	19.56	26.19	34.11	42.40
11	29.21	41.27	27.76	39.21	50.72	3.55	5.01	6.48	0.42	0.60	0.78	0.18	0.26	0.34	0.20	0.28	0.36	16.07	22.70	22.62	31.95	41.33
12	24.24	32.16	30.19	39.90	50.01	4.09	5.34	6.69	0.46	0.61	0.76	0.20	0.26	0.33	0.81	0.30	0.38	15.30	20.22	25.25	33.37	41.83
13	19.67	24.48	36.02	44.84	51.84	4.81	5.99	6.92	0.39	0.48	0.55	0.43	0.54	0.62	0.19	0.24	0.28	10.84	13.50	27.64	34.41	39.78
14	16.28	19.45	37.51	44.81	51.79	5.01	5.99	6.92	0.50	0.60	0.69	0.32	0.38	0.44	0.22	0.26	0.30	11.28	13.47	28.88	34.49	39.86
15	15.90	13.91	37.42	44.50	51.38	5.18	6.16	7.11	0.41	0.49	0.56	0.34	0.41	0.47	0.22	0.26	0.30	11.26	13.39	29.26	34.79	40.17
16	14.55	17.03	37.55	43.94	52.69	5.13	6.01	7.21	0.56	0.65	0.78	0.32	0.37	0.44	0.22	0.26	0.31	14.18	16.60	27.49	32.17	38.57
17	17.13	20.67	37.39	45.21	52.85	4.93	5.95	6.97	0.31	0.38	0.45	0.41	0.49	0.57	0.21	0.25	0.29	12.12	14.62	27.43	33.10	38.77
18	22.95	29.79	34.01	44.14	52.16	4.47	5.80	6.85	0.40	0.52	0.61	0.29	0.37	0.44	0.14	0.18	0.21	11.84	15.37	25.90	33.62	39.73
19	21.90	28.04	33.75	43.22	52.43	4.52	5.79	7.02	0.31	0.40	0.49	0.45	0.58	0.70	0.22	0.28	0.34	13.73	17.58	25.11	32.15	39.01
21-I*	21.99	28.19	31.43	40.30	50.31	4.28	5.49	6.85	0.47	0.60	0.75	0.44	0.57	0.71	0.21	0.27	0.34	15.52	19.90	25.64	32.87	41.04
21-II*	21.99	28.19	32.19	41.27	50.61	4.20	5.38	6.60	0.44	0.57	0.70	0.33	0.42	0.52	0.16	0.20	0.25	14.39	18.45	26.30	33.71	41.34
Ave.	20.88	26.80	33.78	42.61	51.54	4.51	5.68	6.86	0.42	0.53	0.65	0.31	0.39	0.47	0.21	0.26	0.32	13.62	17.38	26.24	33.14	40.14
Std dv	4.55	7.42	3.71	2.53	1.04	0.55	0.41	0.22	0.07	0.09	0.12	0.09	0.11	0.12	0.03	0.04	0.06	2.37	3.82	2.18	1.34	1.24
C.V. %	21.8	27.7	11.0	5.9	2.0	12.3	7.2	3.2	17.5	16.7	19.1	29.6	27.9	26.0	14.9	15.9	20.0	17.4	22.0	8.3	4.1	3.1

*not included in average

ar = as received
d = dry
daf = dry ash free

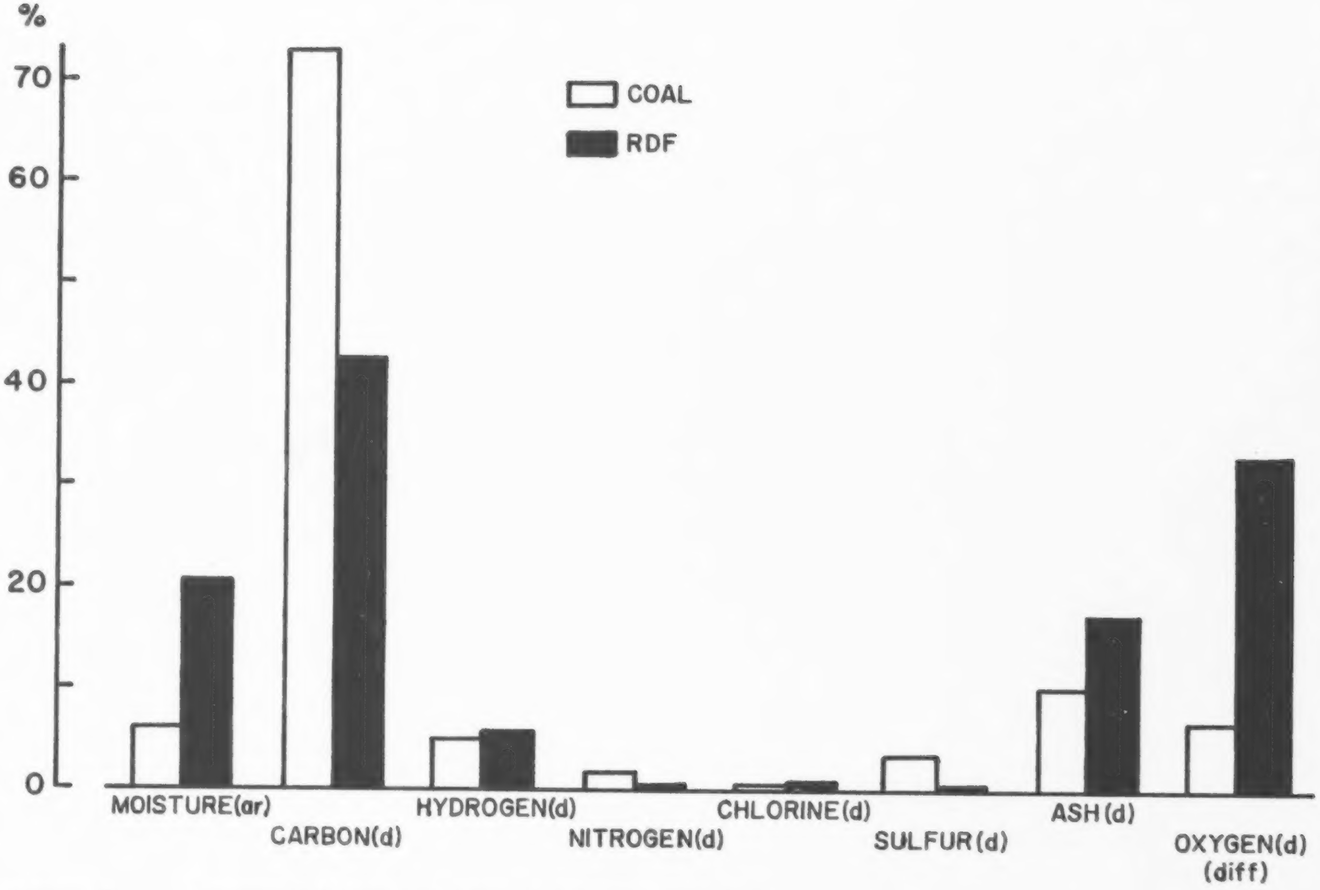

Figure 7. Average Ultimate Analysis of Coal and RDF

factor of 4.5 higher in chlorine than coal. The sources of chlorine in RDF have been given as metal chlorides, such as sodium and calcium chloride, and organochlorides, such as polyvinyl chloride.[16]

The results of the mineral analysis of coal and RDF ash are given in Table 9. Included in the table are also various parameters used to predict fouling and slagging of a fuel. These parameters were developed for coal, so results obtained for RDF should be treated with caution.

The fuel ash from only one run was analyzed for mineral composition, therefore, statements relating to all runs cannot be given. When the calculated parameters given in the last portion of Table 9 are compared to the criteria in Table 10, the following conclusion can be drawn. The T_{250} temperature indicates that both fuels could lead to low to medium furnace slagging. The slagging factor, however, indicated medium slagging from coal firing and, because of the low sulfur content of RDF, a very low slagging factor was calculated for RDF. The application of these parameters to indicate slagging problems from RDF may not be appropriate due to the presence of clear, brown or green ground glass by itself in the co-fired RDF. The initial fusion temperatures of clear glass (1470°F), brown and green glass (1650°F), when not mixed, may promote the presence of soft viscous or sticky material after furnace injection and melting [17].

During an inspection of the boiler interior of December 1980, some slag build-up was noticed on the rear wall, especially around the gas burners, and on the side walls. Samples of this slag were analyzed. The results are given in the section on bottom ash.

All the parameters available for evaluation of fouling problems indicated that severe fouling might be expected from RDF firing and low to medium from coal firing. These parameters were developed for the use on coal ash, not on bottom ash. The high sodium content of RDF is the main reason for the problems that RDF can cause. The convection passes of the boiler were not inspected for

TABLE 9. MINERAL ANALYSIS OF FUEL ASH
(Percent by Weight For Run 18)

MINERAL	COAL ASH	RDF ASH	BLEND*
Silica, SiO_2	45.32	54.30	49.69
Alumina, Al_2O_3	19.48	14.44	17.02
Titania, TiO_2	0.80	1.94	1.36
Ferric Oxide, Fe_2O_3	23.26	6.54	15.11
Lime, CaO	3.70	10.84	7.18
Magnesia, MgO	0.85	2.97	1.88
Potassium Oxide, K_2O	2.13	1.65	1.90
Sodium Oxide, Na_2O	0.55	4.08	2.27
Sulfur Trioxide, SO_3	2.98	1.24	2.13
Phos. Pentoxide, P_2O_5	0.19	1.14	0.65
Strontium Oxide, SrO	0.01	0.00	0.01
Barium Oxide, BaO	0.06	0.09	0.07
Manganes Oxide, Mn_3O_4	0.05	0.34	0.19
Undetermined	0.52	0.43	0.54
	100.00	100.00	100.00
Alkalies as Na_2O, Dry Fuel Basis	0.22	0.80	0.45
Silica Percentage	61.89	72.74	68.86
Base: Acid Ratio	0.47	0.37	0.40
T_{250} temperature, °F	2340	2400	2520
Fouling Factor	0.26	1.51	1.12
Slagging Factor	1.70	0.07	0.57

*estimated on the basis of weight percent of ash from coal and RDF

TABLE 10. SLAGGING AND FOULING CRITERIA

$$\frac{\text{BASE}}{\text{ACID}} = \frac{Na_2O + K_2O + Fe_2O_3 + CaO + MgO}{SiO_2 + Al_2O_3 + TiO_2}$$

Slagging Factor = (BASE/ACID) x (% S on dry coal basis)

Fouling Factor = (BASE/ACID) x (% Na_2O)

Slagging Type	Slagging Factor	T_{250}, °F
Low	≤ 0.6	> 2325
Medium	0.6-2.0	2550-2100
High	2.0-2.6	2275-2050
Severe	>2.6	<2200

Fouling Type	Fouling Factor	%Na_2O in Ash	Alkali % as Na_2O in Coal	Total % Cl in Coal
Low	< 0.2	< 0.5	< 0.3	< 0.2
Medium	0.2 - 0.5	0.5 - 1.0	0.3 - 0.45	0.2 - 0.3
High	0.5 - 1.0	1.0 - 2.5	0.45 - 0.6	0.3 - 0.5
Severe	> 1.0	> 2.5	> 0.6	> 0.5

Source: Coal Fouling and Slagging Parameters (8) fouling, so the severity of possible fouling cannot be assessed.

On a fuel blend basis, i.e. based on the amount of ash from each fuel, the predicted slagging and fouling characteristics based on each fuel will be modified. Low to medium slagging and high to severe fouling might be expected from co-firing of RDF and coal.

The fusion temperatures of the coal and RDF ashes are presented in Table 11. The analyses shows that the HT of RDF ash was higher than the HT of coal ash. This was not expected on the basis of ash fusion temperature analyses performed at Ames, Iowa [17]. The RDF used during the boiler tests at Oscar Mayer & Company had also a much larger difference between initial ash deformation temperature (ID) and fluid temperature (FT) than the Ames RDF ash.

The high ash fusion temperatures of the RDF ash might explain why no serious bottom ash clinkering problems occurred during RDF supplement firing. Some clinkering was experienced at the end of some tests, when the boiler operators switched from burning coal plus RDF to coal only. The clinkers could, however, easily be broken by rodding the bottom-ash bed. Some of the test personnel felt that this was not due to the ash properties, but due to too low underfire air volumes.

Ash Properties

Parameters used to characterize the bottom ash, economizer ash and cyclone ash include: particle size, combustible content, mineral analysis, sulfur, and chlorine content. A discussion of trace elements in the ash from the various sources is given in a separate section.

Particle Size--

Table 12 gives the average particle size distribution of the bottom ash for coal only and coal plus RDF firing. In Figure 8 these two distributions are presented graphically. As the figure shows, the RDF had no significant effect

TABLE 11. FUSION TEMPERATURE OF RDF AND COAL ASH

	COAL	
RUN	6	18
Reducing:		
ID, °F	1980	1940
ST, °F	2150	2120
HT, °F	2200	2170
FT, °F	2450	2420
Oxidizing:		
ID, °F	2100	2060
ST, °F	2500	2530
HT, °F	2550	2580
FT, °F	2700	2680

ID = Initial Deformation Temp.
ST = Softening Temp.
HT = Hemispherical Temp.
FT = Fluid Temp.

			R D F			
Run	10	17	18	21-I	21-II	(Ref. 35)
Reducing:						
ID, ° F	1980	2020	2010	2000	2040	2020
ST, °F	2170	2200	2200	2230	2280	2090
HT, °F	2220	2250	2250	2280	2320	2015
FT, °F	2400	2360	2430	2340	2400	2150
Oxidizing:						
ID, °F	2050	2070	2060	2050	2090	2100
ST, °F	2230	2250	2250	2270	2330	2130
HT, °F	2230	2300	2290	2310	2370	2160
FT, °F	2500	2420	2490	2400	2620	2190

TABLE 12. AVERAGE PARTICLE SIZE DISTRIBUTION OF BOTTOM ASH - PERCENT PASSING SCREEN

		COAL ONLY			COAL + RDF		
Screen	mm	Ave.	Std. dev.	C.V. %	Ave.	Std. Dev.	C.V. %
1 1/2 in.	38.10	97.6	2.8	2.8	97.5	2.4	2.5
1 in.	25.40	92.5	5.6	6.0	92.9	4.6	5.0
3/4 in.	19.05	86.0	7.0	8.1	87.2	6.3	7.3
1/2 in.	12.70	75.1	8.9	11.9	76.4	8.7	11.4
1/4 in.	6.35	53.1	9.3	17.6	54.8	9.5	17.4
#6	3.35	35.8	6.4	17.9	37.6	8.5	22.6

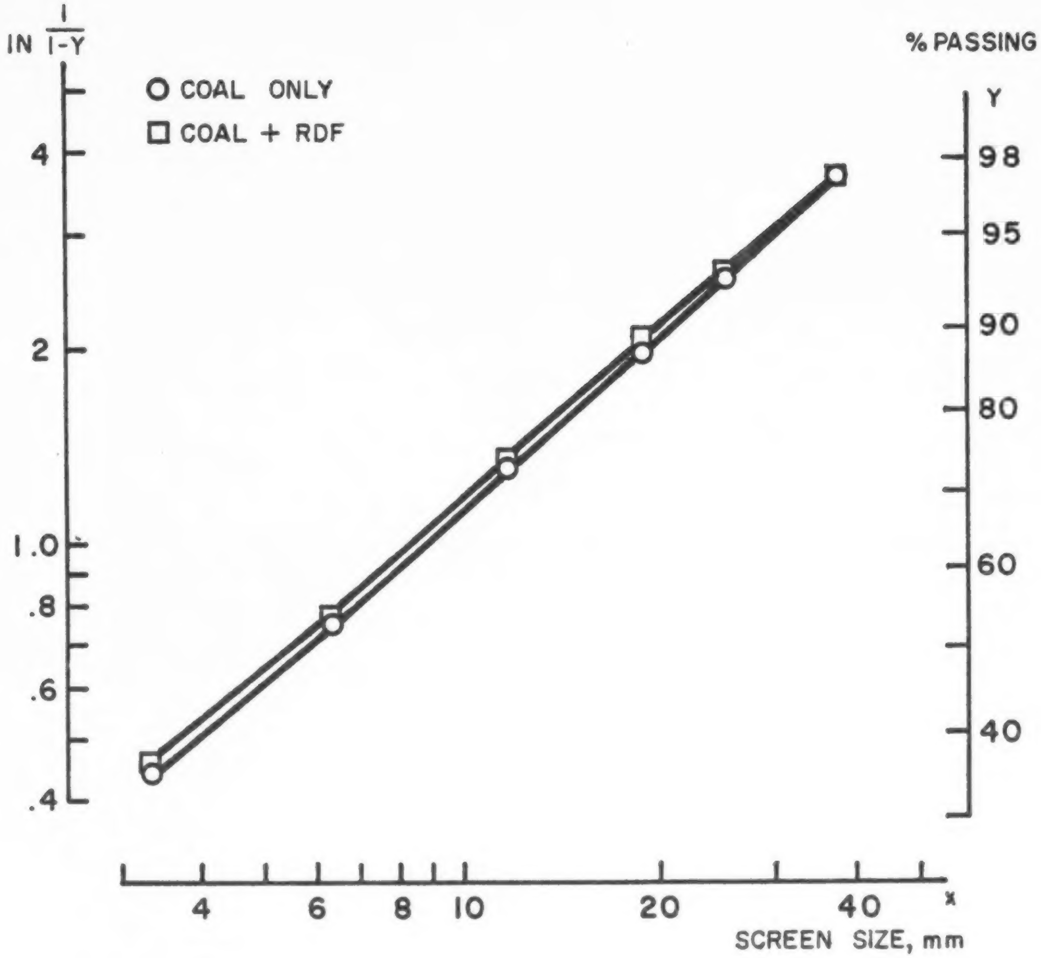

Figure 8. Average Particle Size Distribution of Bottom Ash

on the particle size of the bottom ash. This is also substantiated by the fact that no problems withthe pneumatic ash handling systems were encountered during the RDF and coal co-firing.

The particle size distribution of the economizer ash appeared to be somewhat affected by the replacement of part of the coal by RDF. As shown in Table 13 and Figure 9, on the average a larger fraction of the ash passed the 60 mesh screen (250 mm) when RDF was fired, as compared to coal only. The very finest size fraction (less than 125 mm), however, was not affected. The ash from the RDF co-fired test often contained a few large particles of paper or textile origin. Intuitively, one would expect the particle size of the economizer ash to increase with increasing amount of the higher flue gas velocities through the economizer (generally larger volume of off-gases). However, this did not happen. The reason for this was probably the apparent increase in ash particle density during co-fired tests. The economizer ash from co-fired tests contained a fairly large amount of small, grey, dense particles.

Table 14 summarizes the particle size disbributions of the cyclone ash for coal only and coal plus RDF runs. As shown in Figure 10 there was a substantial decrease in the particle size when RDF was co-fired compared to coal only firing. The reason for this may be the combined effect of higher particle densities and improved collection efficiency of the cyclone with increased gas inlet velocity.

Combustible Content--

Table 15 gives the percent combustibles in the various ashes. Generally the combustible content of the bottom ash was less than two percent. For the efficiency calculations, it is assumed that all the combustible matter in the ash is carbon. In terms of the total carbon input to the boiler, between 0.8 and 1.4 percent was left in the bottom ash. Based on the total input of combustible matter, these percentages are lowered to between 0.5 and 1.0.

TABLE 13. AVERAGE PARTICLE SIZE DISTRIBUTION OF ECONOMIZER ASH - PERCENT PASSING SCREEN

		COAL ONLY			COAL + RDF		
Screen	mm	Avg.	Std. dev.	C.V. %	Avg.	Std. dev.	C.V. %
#12	1700	99.9	0.2	0.2	99.2	0.7	0.7
#14	1410	98.9	0.9	0.9	98.6	1.0	1.0
#18	1000	92.9	4.9	5.2	96.1	1.9	1.9
#20	850	85.5	8.3	9.7	92.9	3.2	3.4
#25	707	74.9	10.2	13.6	85.3	6.1	7.1
#40	420	52.3	11.5	21.9	69.2	9.2	13.3
#50	297	38.6	9.6	24.8	49.6	9.7	19.5
#60	250	29.8	8.0	26.8	36.3	8.9	24.5
#80	177	14.7	4.4	29.7	15.7	5.8	37.0
#120	125	5.7	2.0	34.4	5.7	3.2	56.0

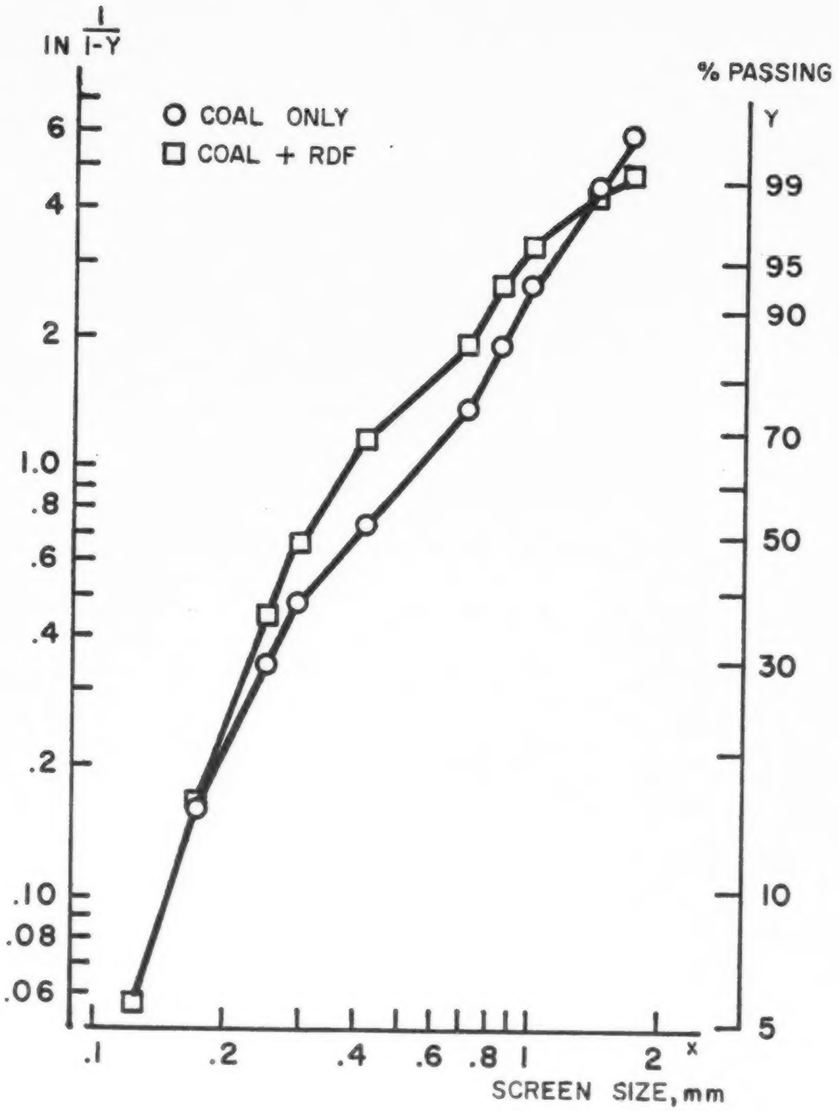

Figure 9. Average Size Distribution of Economizer Ash

TABLE 14. AVERAGE PARTICLE SIZE DISTRIBUTION OF CYCLONE ASH - PERCENT PASSING SCREEN

		COAL ONLY			COAL + RDF		
Screen	mm	Avg.	Std. dev.	C.V. %	Avg.	Std. dev.	C.V. %
#25	707	98.7	0.5	0.5	98.8	1.3	1.3
#40	420	91.7	2.3	2.5	96.0	2.1	2.2
#50	297	84.8	3.5	4.1	91.8	4.4	4.8
#60	250	80.4	4.0	5.0	88.9	5.3	6.0
#80	177	68.3	7.2	10.5	78.4	7.5	9.5
#120	125	55.4	8.7	15.7	64.2	8.9	13.8
#170	88	42.9	9.1	21.2	52.3	9.3	17.8
#200	74	32.5	7.8	23.9	43.0	10.9	25.4
#230	63	20.8	5.1	24.4	30.5	13.7	44.9

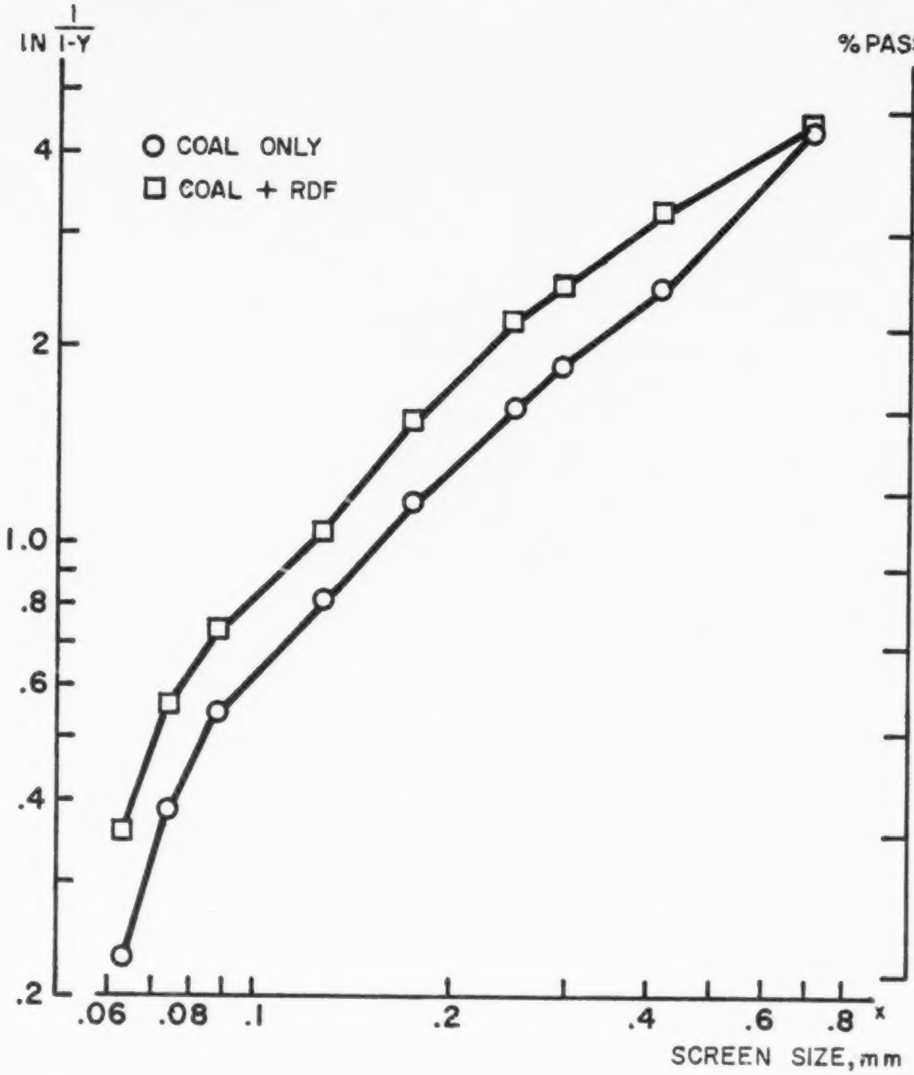

Figure 10. Average Size Distribution of Cyclone Ash

TABLE 15. SUMMARY OF COMBUSTIBLES IN THE ASH

Run	Steam Load lb/hr	Steam Load by RDF (%)	Bottom Ash %	Economizer Ash %	Cyclone Ash (%)	Fly (%)
1	88,700	0	2.2	63	42	58
2	-	0	-	-	-	-
3	110,000	0	1.4	36	37	68
4	107,700	0	2.1	42	38	37
5	99,300	0	0.9	27	28	-
6	98,700	0	0.6	43	32	-
7	100,000	0	-	-	-	61
8	78,200	0	2.1	33	27	69
9	78,000	23	0.9	16	19	40
10	84,800	12	0.8	29	18	29
11	102,100	30	0.5	27	20	26
12	100,000	45	1.8	21	8	-
13	98,600	37	1.7	23	20	23
14	94,000	48	1.2	19	16	18
15	73,400	30	1.4	12	27	25
16	86,500	48	2.0	8	13	13
17	98,800	29	1.1	12	29	-
18	98,800	27	2.3	17	17	29
19	89,700	16	1.2	15	21	43
20	99,100	0	1.1	22	27	51
21	87,100	20	2.4	23	28	31

Plots of the combustible content in bottom ash versus steam load (see reference[6]) and percent RDF heat input respectively, indicated no definite trends.

The percent combustibles in the economizer and cyclone ash are also given in Table 15. Figures 11 and 12 show that there was a decrease in the combustible content of both economizer and cyclone ash when larger amounts of coal were replaced by RDF. The reason for this may be that since RDF has less fixed carbon and more volatile matter than coal, a more complete burn-out of RDF and coal takes place. The fly ash also shows a significant decrease in combustibles when the RDF replacement rate is increased, as will be discussed later.

Mineral Analyses of Ash and Slag--

Two mineral analyses of the bottom ash were performed, one on an ash from a coal-only run and one on an ash from a run with 45 percent of the heat input provided by RDF (an RDF to coal mass input ratio of about 1.8). No mineral analyses were made on economizer or cyclone ash. Table 16 gives the results of these analyses. Some of the values were unexpected, especially the lower silica and higher ferric oxide content of the ash from the co-fired run. Based on the analyses of coal and RDF ash presented previously (Table 9), these values would be expected to be higher and lower, respectively, than the values from the coal-only run. The mineral composition of the fuel ash, especially the RDF ash, may vary substantially, as indicated by the elemental analyses.

By comparing the total sodium, the fouling factor, and the T_{250} temperature with the criteria given in Table 10, it is apparent that the bottom ash from the coal + RDF has a higher potential for both fouling and slagging than the ash from the coal only run. However, these results should be interpreted with caution since the parameters were developed for the use on coal ash, not on bottom ash.

Included in Table 16 are also mineral analyses of two slag samples. Refractory slag refers to deposits on the refractory between the boiler tubes, and

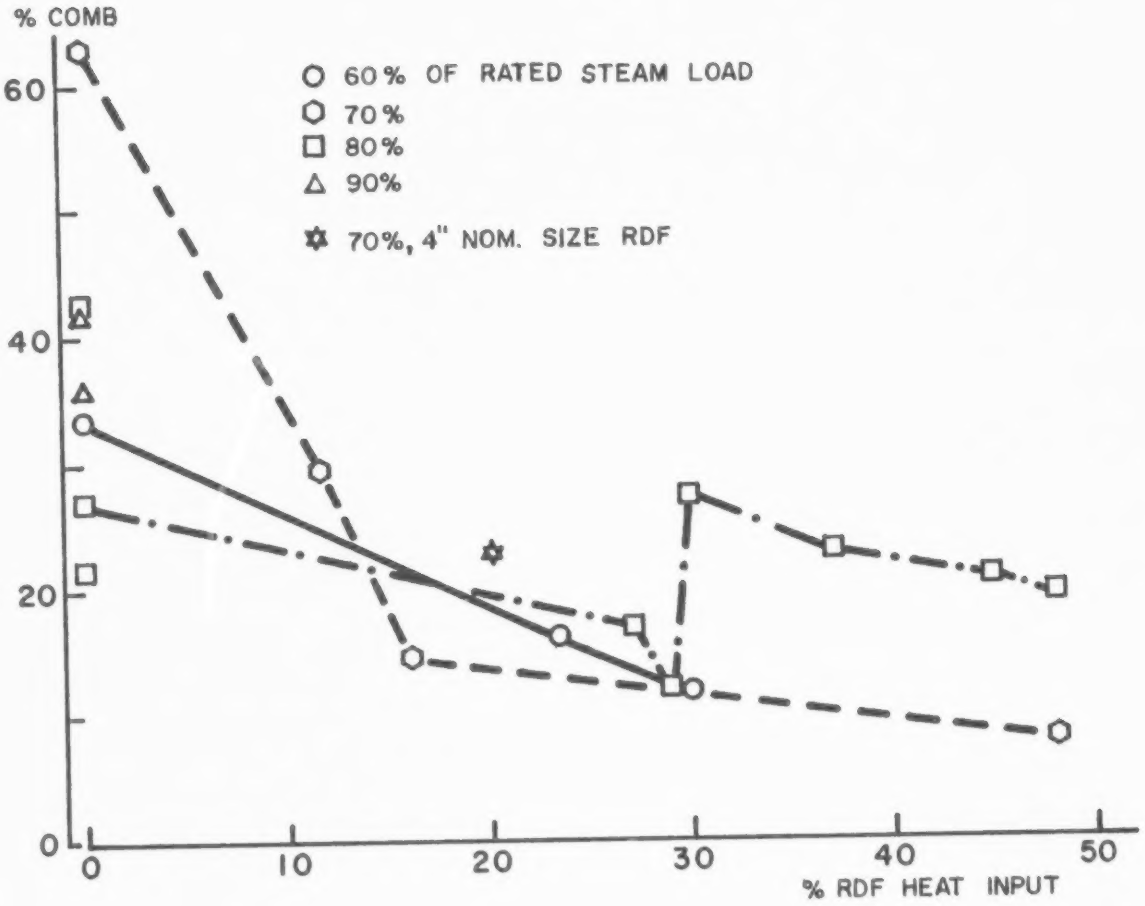

Figure 11. Effect of RDF Heat Input on Combustible Content in Economizer Ash

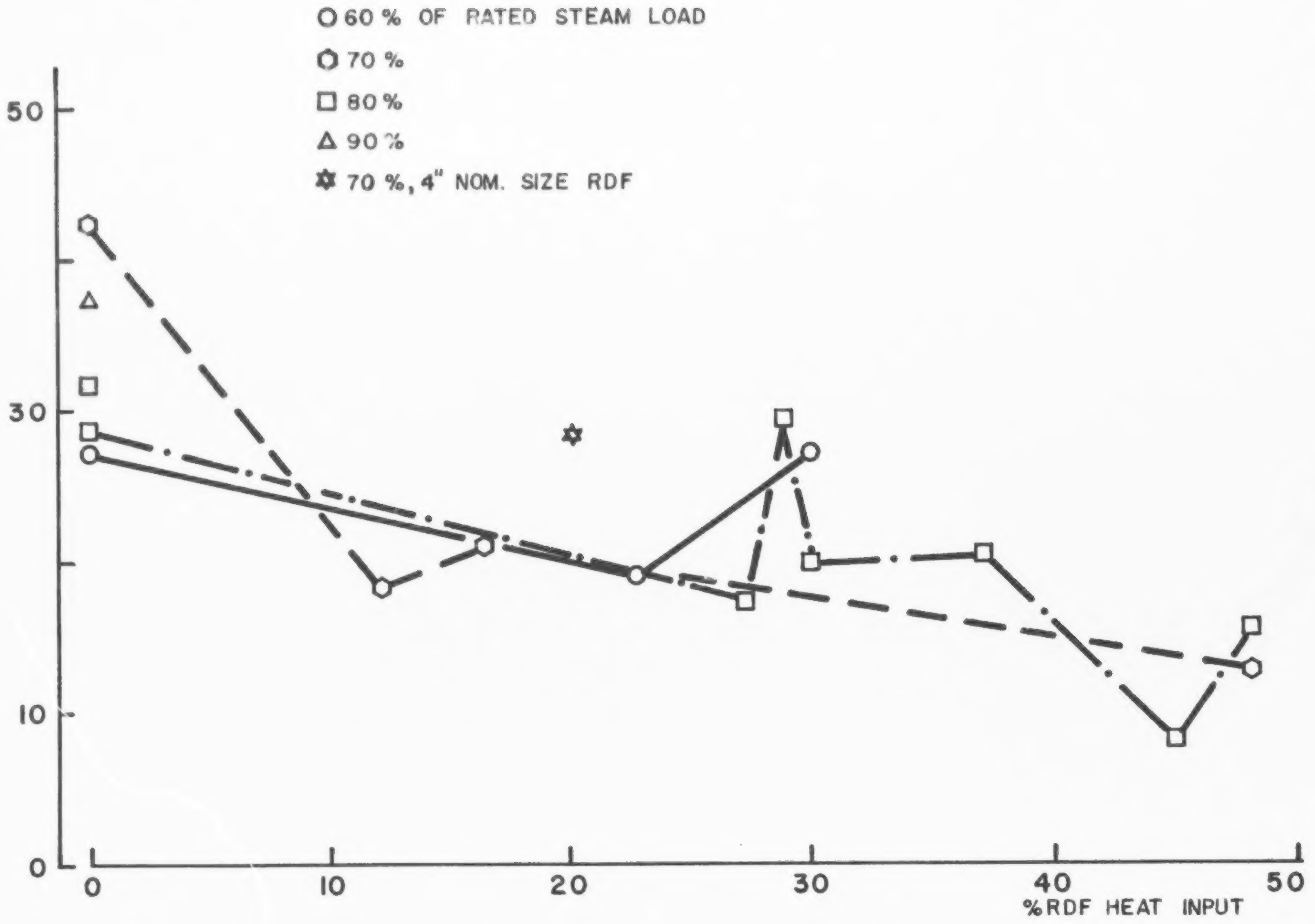

Figure 12. Effect of RDF Heat Input on Combustible Content in Cyclone Ash

TABLE 16. MINERAL ANALYSIS OF BOTTOM ASH AND SLAG

	BA Run #6	BA Run #12	Refractory Slag	Tube Slag
SiO_2	49.72	46.39	39.47	43.13
Al_2O_3	21.67	19.67	18.75	14.77
TiO_2	1.10	0.97	0.90	1.50
Fe_2O_3	22.20	23.30	33.30	22.19
CaO	1.04	3.39	2.96	7.71
MgO	0.72	1.04	0.83	1.92
$V_{12}O$	1.95	1.92	1.85	1.66
Na_2O	0.27	1.35	0.72	2.27
SO_3	0.14	1.39	0.38	3.97
P_2O_5	0.04	0.43	0.10	0.31
BaO	NO	0.05	-	-
Mn_3O_4	NO	0.10	-	-
Undet.	1.15	0.00	0.74	0.57
	100.00	100.00	100.00	100.00
BASE				
ACID	.36	0.46	0.67	0.60
% S	0.14	0.38		
Slagging Factor	0.05	0.17		
Fouling Factor	.10	0.62	0.48	1.36
T_{250} °F	2520	2310	2200	2300

tube slag refers to deposits on the tubes. The samples were taken in December 1980, after about 180 tons of RDF had been co-fired. Because no analyses of slag before RDF and coal were co-fired exist, one can only compare the two types of slag. An interesting observation is the high alkali, magnesia, lime, and sulfur trioxide content of the tube slag when compared to the refractory slag. From periodic inspections of the boiler, the tube slag is thought to be more recently deposited than the refractory slag.

Sulfur and Chlorine--

Data on sulfur and chlorine analyses from the three types of ash are presented in Table 17. The sulfur content of the bottom, economizer and cyclone ash tended to increase with increasing RDF replacement, which at first appears to be unexpected since RDF has a lower sulfur content. The RDF has a higher proportion of calcium and magnesium than coal, and consequently, the ash from co-fired tests would contain more of these elements. Sulfur reacts with the calcium and magnesium in the ash to form calcium and magnesium sulfate. However, at most only 3% of the sulfur has reacted with the ash.

Similarily the chlorine content of the ash tended to increase with increasing RDF replacement. However, the removal effect is small.

Boiler Operating Conditions

Steam loads ranged from 73,400 lb of steam/hr to 102,100 lb of steam/hr during the tests. On the average, the steam load varied from the designated test load by 3500 lbs of steam/hr which represents a variance from the designated test load of 3.4% to 4.7%. The change of the steam load was due to variability of the RDF feed.

Several operating restrictions dictated the loads at which the boiler could be tested. A minimum steam load of 45,000 lb steam/hr on coal was maintained on the boiler at all times to reduce the chance of boiler flame out and heavy

TABLE 17. TOTAL SULFUR AND CHLORINE IN ASH (DRY BASIS)

Run #	% RDF Heat Input	% of rated Steam Load	% SULFUR BA[1]	% SULFUR EA[2]	% SULFUR CA[3]	% CHLORINE BA	% CHLORINE EA	% CHLORINE CA
6	0.0	79.0	0.14	0.65	0.60	0.03	0.02	0.01
10	12	67.8	0.15	--	--	0.01	--	--
11	30	81.7	0.15	0.58	1.37	0.01	0.05	0.04
12	45	80.0	0.38	0.94	1.07	0.01	0.04	0.09
15	30	58.7	0.24	--	--	0.03	--	--
16	48	69.2	0.30	--	--	0.02	--	--
18	27	79.0	0.96	0.95	1.76	0.02	0.04	0.04
21	20	69.7	0.24	0.68	0.37	0.04	0.06	0.05

1) BA = Bottom Ash
2) EA = Economizer Ash
3) CA = Cyclone Ash

smoking if RDF feed was interrupted. Operation of boiler at higher loads was limited to 110,000 lbs steam/hr to minimize the chance of overload or surge and reduce the possibility of smoking. These loading conditions established the firing range for the 21 tests that were conducted.

Table 18 summarizes the air flow measurements. Fluctuation of air flow during the tests and non-uniform flow in the ducts and stack were the major contributing factors to a total uncertainity of about 12% in stack gas and inlet air flow measurements. Combustion gases released from the coal and RDF contributed about 15,000 CFM to the stack gas flow at a firing rate of 100,000 lbs steam/hr. Considering this contribution, the inlet and exhaust gas measurements agree within the error bounds. Measurement uncertainties precluded using the difference between inlet and outlet air flows to diagnose air leaks into the boiler.

The coal runs, overfire air and RDF feed air flows combined, averaged 26% of the total inlet air. For coal co-fired with RDF this average increased to 40% with a low of 35% and a high of 47%. These latter values are considerably higher than the recommended range of 20% to 25% overfire air.

The average underfire air plenum pressure was 0.25 inches H_20. Design underfire air plenum pressure is 1.5 inches H_20 at a firing rate of 100,000 lbs steam/hr.

The underfire air plenum pressure was substantially below design value for all tests. This is due to two factors: (1) the ID fan could not handle more underfire air since the overfire air flow was so great, and (2) spot measurements indicated about 30% of the underfire air flow is diverted through the gas burners for cooling purposes even when they are shut off. The gas burner cooling air is tramp air and increases the total boiler air by about 20%. For a stack temperature of 400°F and inlet air temperature of 80°F,this tramp air reduces

TABLE 18. AIR FLOW MEASUREMENTS SUMMARY

Run #	Steam Load lbm Steam/hr	% RDF (heat input basis)	Underfire Air SCFM	Overfire Air SCFM	RDF Feed Air SCFM	Total Inlet Air SCFM	Total Exhaust Air SCFM	Excess Air %	Stack Temp. °F
3	110,000	0	27,500	9,800	300	37,600	39,600	63	415
4	107,700	0	29,900	11,300	300	41,500	43,000	57	430
5	99,300	0	22,600	8,100	300	31,000	---	58	420
6	98,700	0	24,700	8,500	300	33,500	39,900	55	425
7	99,100	0	---	---	---	---	39,300	66	425
8	78,200	0	24,500	7,300	300	32,100	31,300	69	405
9	78,000	46	22,800	6,400	6,700	35,900	36,300	84	415
10	84,760	27	20,900	6,900	6,600	34,400	43,300	106	425
11	102,100	55	18,900	9,300	6,400	34,600	47,400	74	430
12	100,000	68	16,800	7,600	6,800	31,200	42,300	73	435
13	98,600	54	24,000	9,100	6,000	39,100	41,400	71	435
14	94,000	65	23,900	6,900	6,200	37,000	40,800	88	435
15	73,400	48	20,500	6,200	5,700	32,400	37,800	109	410
16	86,500	66	21,400	7,900	6,400	35,700	40,300	55	430
17	98,800	45	21,900	7,600	6,500	36,000	44,400	75	435
18	88,800	45	18,900	8,900	7,900	35,700	44,500	70	440
19	89,700	30	18,200	7,800	7,000	33,000	43,800	76	435
20	99,100	0	25,000	8,400	300	33,700	39,900	61	420
21	87,100	36	23,700	7,300	7,400	38,400	42,400	115	435

the boiler efficiency by about 1.3%. For a boiler operating continuously at 80,000 lb steam/hr, the cooling air through the gas burners costs about $28,000 per year.

Another effect of reduced plenum pressure is less efficient burning of the coal on the grates. At plenum pressures substantially below design there is insufficient air velocity through the grate holes and the fire tends to be "lazy". Combustion on the grates is inadequate and smoke increases. Increasing overfire air can compensate for this but will reduce the efficiency by increasing excess air more than is really necessary.

Excess air measurements listed in Table 18 range from 55% to 115%. This high excess air can be reduced by:

1. Increasing underfire air plenum pressure;
2. Reducing cooling air to the gas burners to the minimum. (Increasing plenum pressure will increase gas burner cooling air also. Thus, minimal adjustment would be to achieve initial flow for cooling);
3. Decreasing overfire air;
4. Sealing air leaks around boiler. (Smoke tests indicated several air leaks around the base of the boiler.);
5. Maintaining grate seals. Underfire air must go through grate holes, not around grate edges.

Reducing excess air will improve efficiency and reduce stack temperatures. However, the economizer should be operated such that the flue gas temperature at the outlet is greater than 320°F. This can be done by by-passing a fraction of the feedwater. For high sulfur fuels, the stack temperature must be at least 320°F to prevent condensation of SO_3.

Subsequent to the 21 stack tests, conducted between July 9, 1980, and May 5, 1981, Oscar Mayer personnel have been attempting to reduce the O_2 levels in the stack gases and reduce the stack temperature. Reducing the overfire air on the boilers front wall has proven to be the most effective measure in reducing the O_2 levels and the stack temperature of the exhaust gases.

Boiler Efficiency Data

The results of the boiler efficiency determination for each test run are summarized in Table 19. Since the boiler efficiency was determined from the heat loss method, the dry gas loss, the fuel moisture, combustion moisture and carbon heat loss are also given in Table 19. ASME test forms for the efficiency test for each test run are given in Appendix B.

Boiler efficiency (based on higher heating value of coal and RDF) is plotted versus % RDF heat input in Figure 13. The least squares regression line for the data and the 95% confidence intervals are drawn on the graph. The slope of the regression line is -0.107 with a standard deviation of 0.0207. The regression line is highly significant. The boiler efficiency decreased by 1% for each 10% increase in heat output due to RDF when the higher heating values are used.

Figure 14 is a plot of lower heating value (LHV) efficiency versus percent RDF heat input. Contrary to the HHV efficiency plot, this plot shows no significant decrease in efficiency with increasing RDF heat input. (A horizontal line can be placed within the 95% confidence interval.) Hence, the main reason for the decrease in boiler efficiency with increased RDF heat input was the higher heat loss due to moisture when co-firing RDF.

Figure 15 shows that the percent excess air had a slightly significant effect on the LHV boiler efficiency. However, it was not as significant as the effect of higher fuel moisture with increasing amounts of RDF.

In Figure 16 the LHV efficiencies are plotted versus steam load. There was a tendency for improved boiler efficiency with increased steam load. However, because of the scatter of the data points, the increase cannot be said to be significant.

TABLE 19. HEAT LOSSES AND BOILER EFFICIENCY

Run #	Steam load (lb/hr)	Steam load % of rated capacity	% RDF heat basis	% RDF mass basis	Dry gas	% heat loss due to Moisture in fuel	% heat loss due to H_2O from comb. of H	Comb. in ashes	Boiler Efficiency %
3	110,000	88.0	0	0	13.24	0.43	4.19	1.43	80.0
4	107,700	86.2	0	0	12.83	0.51	4.16	1.16	80.7
5	99,300	79.4	0	0	13.64	0.49	4.15	0.81	80.2
6	98,700	79.0	0	0	12.48	0.68	4.23	0.74	81.2
7	99,100	79.3	0	0	12.65	0.60	4.17	0.87	81.0
8	78,200	62.6	0	0	13.18	0.47	4.15	1.27	80.3
9	78,000	62.4	23.1	46.0	14.83	1.90	5.41	1.34	75.8
10	84,800	67.0	11.5	27.4	17.77	1.16	4.86	0.93	74.6
11	102,100	81.7	29.5	55.6	14.77	2.86	5.36	1.23	75.1
12	100,000	80.0	45.0	68.4	12.71	3.01	6.41	1.13	76.1
13	98,600	78.9	36.6	54.4	12.55	1.96	5.81	0.98	78.0
14	94,000	75.2	47.9	65.4	13.92	1.80	6.25	0.83	76.5

(continued)

TABLE 19. concluded

Run #	Steam load (lb/hr)	Steam load % Of rated capacity	% RDF heat basis	% RDF mass basis	% heat loss due to Dry gas	% heat loss due to Moisture in fuel	% heat loss due to H_2O from comb. of H.	Comb. in ashes	Boiler Efficiency %
15	73,400	58.7	30.4	48.4	14.28	1.33	5.68	0.84	77.2
16	86,500	69.2	48.0	66.0	16.02	1.62	6.46	0.85	74.4
17	98,800	79.0	29.1	45.0	13.69	1.38	5.49	1.04	77.7
18	98,800	79.0	27.1	45.1	14.10	1.88	5.32	1.10	76.9
19	89,700	71.8	16.4	30.5	13.16	1.23	4.94	1.01	79.0
20	99,100	79.3	0	0	11.35	0.86	4.16	0.82	82.1
21	87,800	69.7	36.5	20.3	14.66	1.72	5.07	1.39	76.5

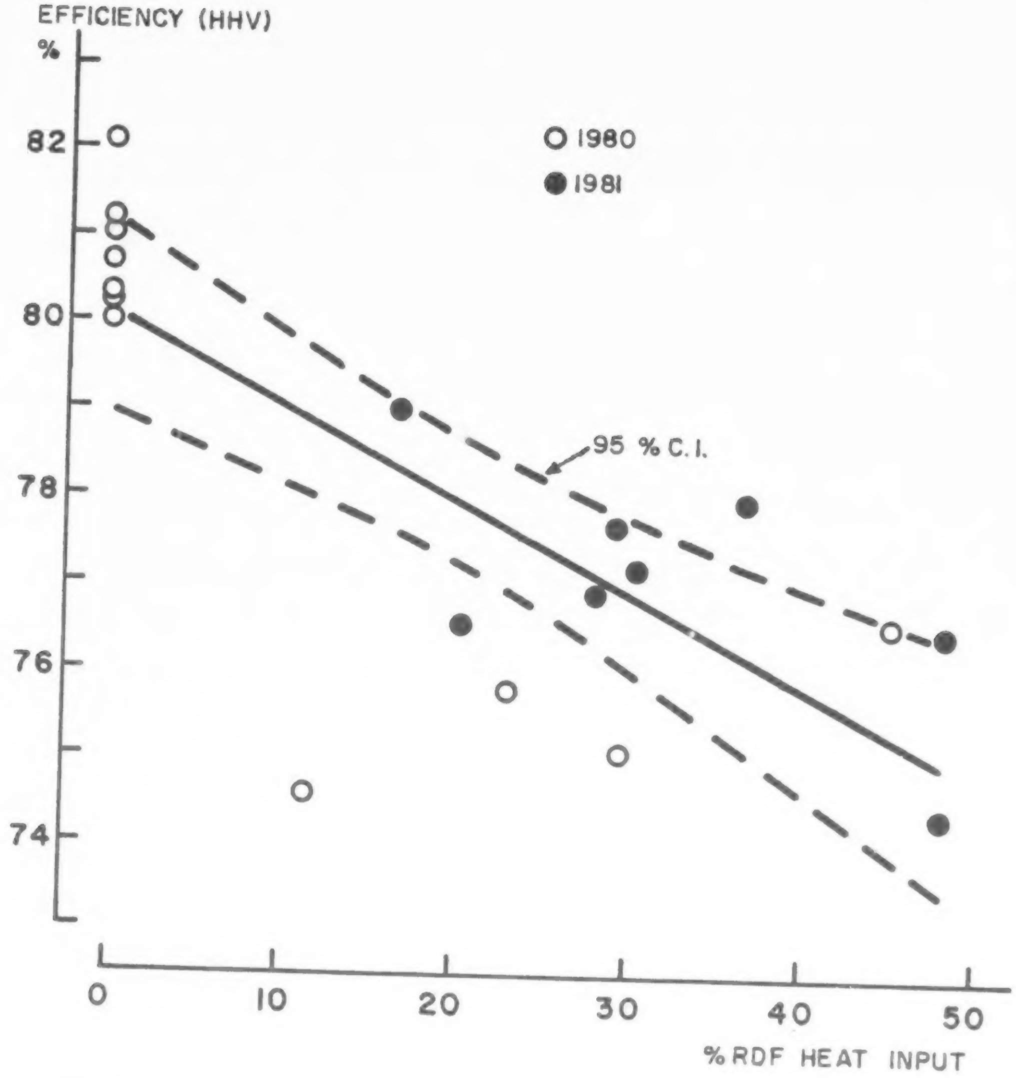

Figure 13. Effect of RDF Heat Input on Boiler Efficiency (based on higher heating value)

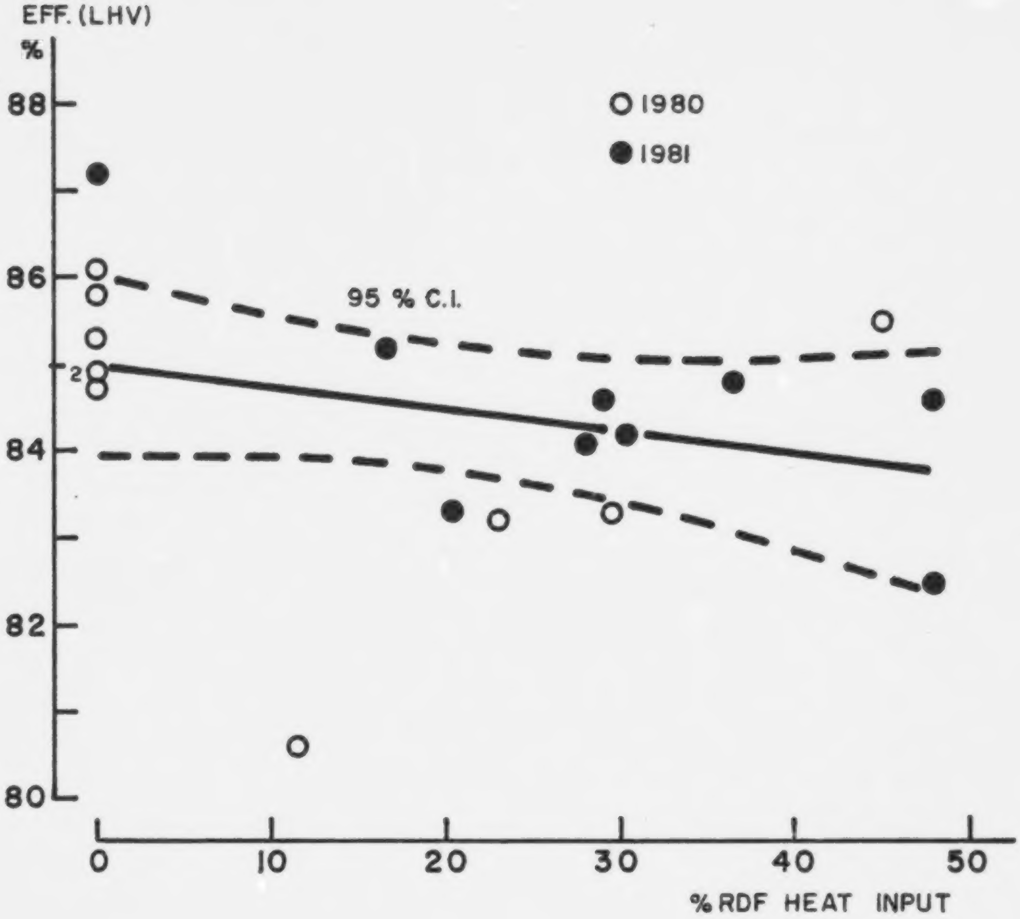

Figure 14. Effect of RDF Heat Input on Boiler Efficiency (based on lower heating value)

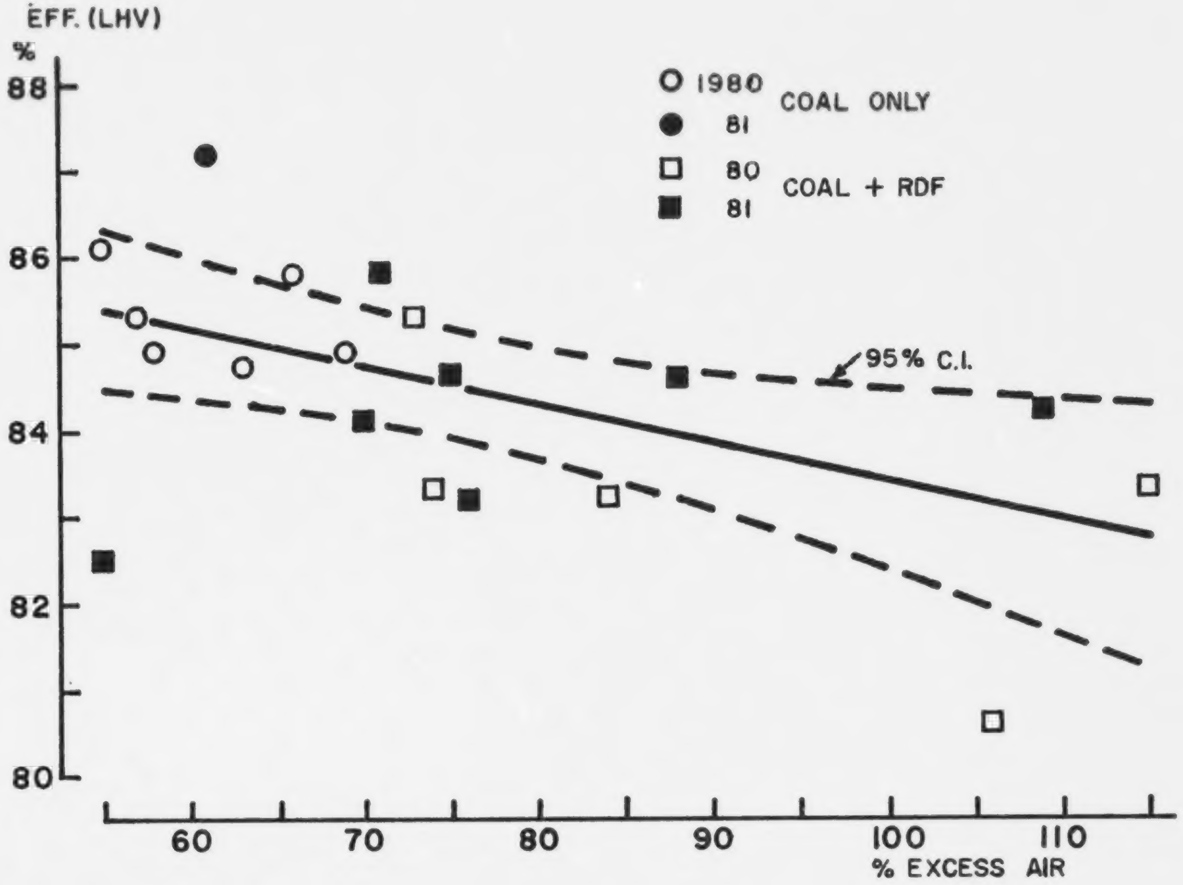

Figure 15. Efficiency (based on lower heating value) vs. Percent Excess Air

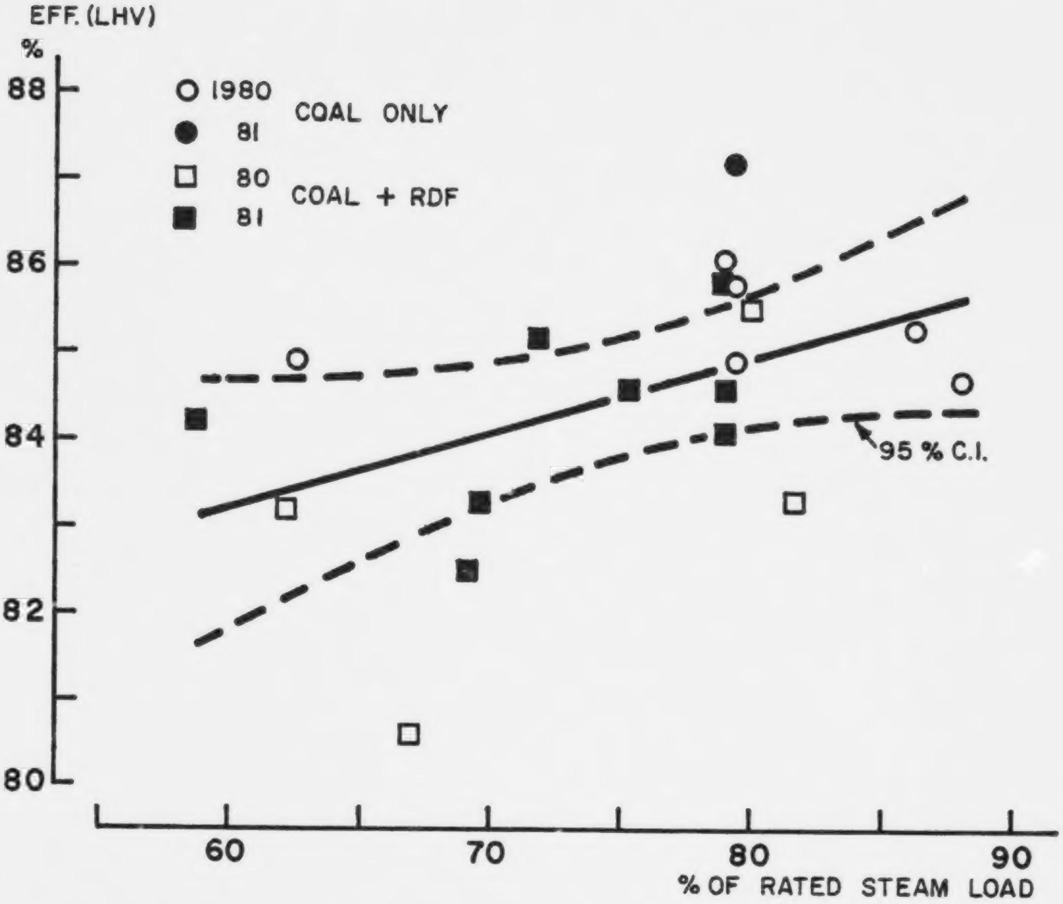

Figure 16. Efficiency (based on lower heating value) vs. Steam Load

Total Particulate Emmissions

The stack sampling data for total particulate emissions is summarized for each of the test runs in Table 20. The complete test conditions for each run are given in Appendix C at the end of the report. The particulate emissions are reported in grains per wet standard cubic foot of stack gas (wscf), which is obtained directly from stack tests, and as pounds per million Btu of heat input, which depends on the boiler efficiency. The latter is the most universal measure of particulate emissions.

There were 6 coal only particulate emissions tests which ranged from 0.64 to 0.80 lb/10^6 Btu. There were 12 coal plus RDF particulate emissions tests which ranged from 0.60 to 1.28 lb/10^6 Btu. Coal plus RDF tests which were run in the Fall of 1980 exhibited significantly higher particulate emissions than the tests run in the Spring of 1981. This could be because during the Fall the ash content of the RDF averaged 21.6% on a dry basis, whereas the RDF in the Spring averaged 14.9% (excluding Run 21). The fuel processing plant was not changed so that this probably represents a seasonal change in ash which may influence particulate emissions. Also, during the Fall tests, large flakes of ash were observed to be intermittently expelled from the stack. Some of these may have influenced the particulate data. The flakes were thought to have come from the upper ducting and stack walls and not the stoker. The flaking appeared to occur primarily for an hour or so after boiler conditions were changed. In the Spring the boiler was allowed to steady-out for an hour after the RDF was introduced and the flaking was not as observable during the testing.

Particulate emissions are plotted versus percent RDF (on a heat-input basis) in Figure 17. A linear regression line is plotted using all the data, which shows a slight increase in particulate emissions with % RDF. However the 95% confidence lines for the slope of the line are also plotted, and it is evident

TABLE 20. SUMMARY OF PARTICULATE EMISSIONS

Run	Steam load (lb/hr)	Steam Load by RDF (%)	Excess air (%)	Emissions (grains/wscf)	Emissions (lb/10^6 Btu)
1	88,700	0	72	0.32	-
2	82,000	0	-	-	-
3	110,000	0	63	0.29	0.64
4	107,700	0	57	0.32	0.76
5	99,300	0	58	-	-
6*	98,700	0	55	0.26	0.64
7	100,000	0	66	0.32	0.80
8	78,200	0	69	0.26	0.63
9*	78,000	23	84	0.32	0.87
10	84,800	12	106	0.38	1.10
11	102,100	30	74	0.37	0.97
12	100,000	45	73	0.52	1.28
13*	98,600	37	71	0.30	0.76
14	94,000	48	88	0.27	0.69
15	73,400	30	109	0.21	0.63
16	86,500	48	55	0.30	0.79
17	98,800	29	75	0.26	0.70
18	98,800	27	70	0.30	0.79
19	89,700	16	76	0.24	0.71
20	99,100	0	61	0.29	0.74
21	87,100	20	115	0.21	0.60

*one traverse used

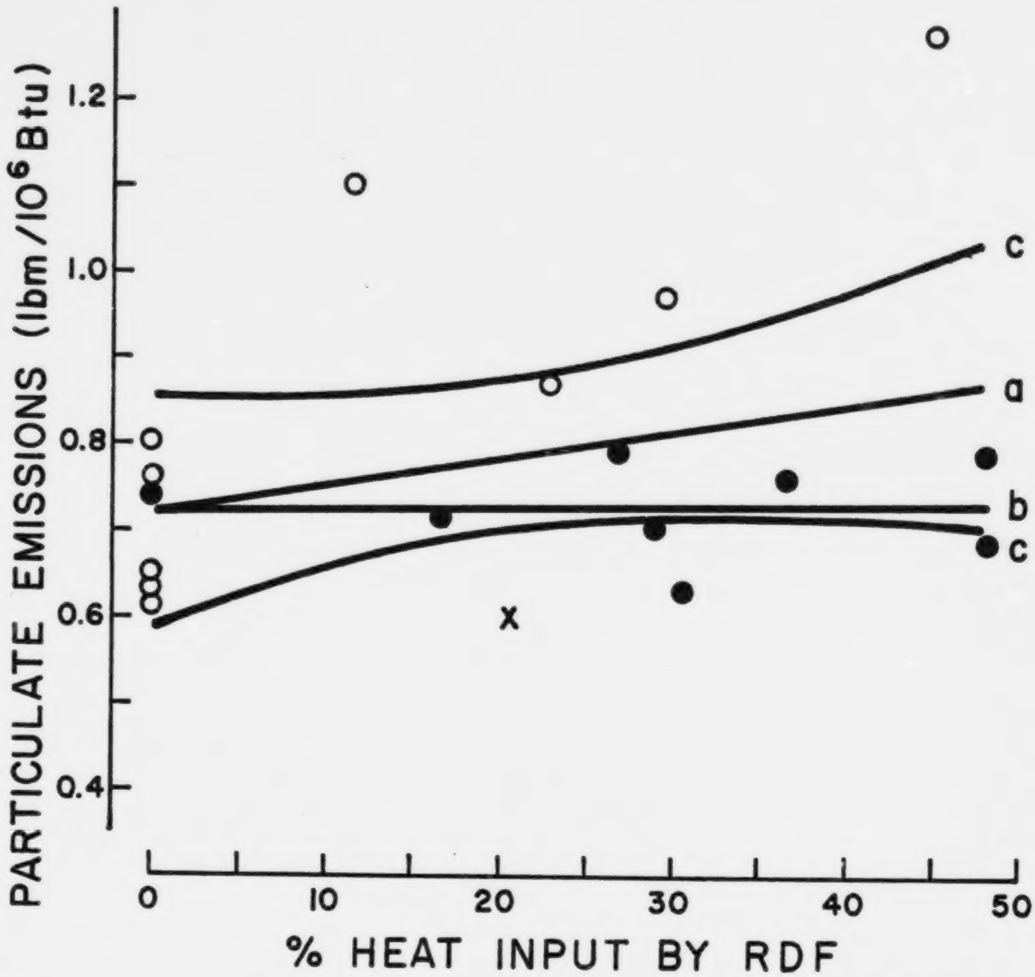

Figure 17. Particulate Emissions Versus Heat Input from Refuse Derived Fuel. (Open circles are 1980 data. Closed circles are 1981 data. X represents 4 inch nominal size RDF, Run 21. a is linear fit using all data except Run 21. b is linear fit excluding 1980 RDF data and Run 21. c is 95% confidence interval for a.

that the slope of the plotted line is not statistically significant due to the scatter of the data. If the 1980 RDF data is excluded, the linear regression line has a zero slope indicating no increase of particulate emissions with increasing RDF. The conclusion is that the particulate emissions are not significantly increased in this boiler (which has been setup to burn RDF), by burning RDF at up to 50% replacement rates. The average particulate emissions, excluding the 1980 RDF data, were 0.72 $lb/10^6$ Btu.

No significant trend was observed between boiler load and particulate emissions. However, the range of boiler loads that could be run was not large.

One run was made with an RDF nominal top size of 4 inches (Run 21) as compared to all the other test runs which used a nominal top size of 2 inches. This test had particulate emissions of 0.60 $lb/10^6$ Btu which was the lowest of any of the tests conducted.

Particulate emissions are influenced by unburned carbon carryover. The coal only tests averaged 57% combustibles in the fly ash whereas the tests with RDF averaged 24% combustibles in the fly ash (see Table 15). This may be due to the increased volatile combustion when burning RDF. This effect helps to explain why the particulate emissions do not increase when burning RDF even though the total ash increases.

Particulate emissions may be influenced by the excess air, underfire air and overfire air. Excess air is needed to burn out the carbon. However, too much air will decrease the residence time of the suspended fuel particles. Underfire air controls burn-out of the bottom ash. Overfire air controls burn-out of the suspended particles. These parameters were set by the boiler operators, as discussed in the previous section, and could not be controlled explicitly.

The size distribution of the fly ash was measured on 5 different occasions and representative results are reported in Table 21. There was no dramatic dif-

TABLE 21. CASCADE IMPACTOR MEASUREMENTS OF FLY ASH: CUMULATIVE PERCENT LESS THAN d_{50}

d_{50}(microns)	Coal only (Run 2)	45% RDF (Run 17)*
5**	22	20
2	14	16
1	10	13
0.6	7	11
0.3	5	8

*45% RDF by weight or 30% of heat load by RDF

**BUCRA cyclone catch

ference between the coal only and the 55% coal plus 45% RDF run although the latter had a higher percentage of sub-micron particles. The fact that 80% of the mass was greater than 5 microns indicates that inspection, further testing and possible replacement of the cyclone collector should be considered.

Gaseous Emission - SO_2, HCl, CO, NO

The sulfur dioxide concentrations which were measured are shown in Table 22. These values are considered to be incorrect due to experimental errors which could never be located and eliminated. Measurement of sulfur in the ash showed that only a few percent of the fuel sulfur was removed in the ash. Essentially all of the fuel sulfur will be emitted as sulfur dioxide. In this case the stack gas concentrations should be several times greater than was measured. Since the RDF averaged 0.26% sulfur (as received) and the coal averaged 3.51% sulfur, the sulfur dioxide emissions will decrease as the coal is replaced by RDF. For example, Run 6 (100% coal) would emit 4.3 lb $SO_2/10^6$ Btu while Run 16 (48% of heat load by RDF) would emit 2.6 lb $SO_2/10^6$ Btu.

The hydrogen chloride emissions which were measured are shown in Table 23. The stack concentrations with coal only averaged 225 ppm (corrected to 3% O_2), while the concentrations with the coal plus RDF runs ranged from 200 to 500 ppm. The coal averaged 0.15% chlorine (as received), while the RDF averaged 0.31% chlorine. About 1% of the chlorine was removed in the ash. Although there is scatter in the data, the conclusion is that chlorine in the fuel is emitted completely as hydrogen chloride. The measured emission rates averaged 0.26 lb $HCl/10^6$ Btu for coal only and averaged 0.33 lb $HCl/10^6$ Btu for the coal plus RDF runs.

The carbon monoxide concentrations in the stack gas are low for both the coal and the coal plus RDF tests as summarized in Table 24. This is to be expected with the high excess oxygen in the stack gas which ranged from 8 to 11%.

TABLE 22. SUMMARY OF SO_2 EMISSIONS

Run	Steam Load (lb/hr)	Effective % S in Fuel	SO_2 Conc.* (ppm)	SO_2 Conc. * Corrected to 3% O_2 (ppm)
3	110,000	3.4	507	690
4	107,700	3.3	263	345
6	98,700	2.8	386	500
8	78,200	3.3	605	790
9	78,000	2.0	131	170
10	84,800	2.5	391	630
11	102,100	1.2	276	390
12	100,000	1.3	213	300
14	94,000	-	310	430
15	73,400	1.5	314	510
16	86,500	1.1	304	460
17	98,800	2.1	381	540
19	89,700	2.3	(780)	1090
20	99,100	3.0	272	360
21	87,100	2.1	773	1290

---

* Values considered to be in error.

TABLE 23. SUMMARY OF HCl EMISSIONS

Run	Steam Load (lb/hr)	Effective % Cl in Fuel	HCl Conc (ppm)	HCl Conc. Corrected to 3% O_2 (ppm)	HCl Emissions ($lb/10^6$ Btu)
4	107,700	0.15	210	275	0.30
8	78,200	0.15	132	175	0.23
9	78,000	0.23	210	275	0.33
11	102,100	0.16	286	400	0.47
12	100,000	0.19	180	250	0.27
15	73,400	0.25	311	506	0.59
16	86,500	0.27	165	250	0.26
17	98,800	0.29	142	200	0.22
18	98,800	0.22	179	250	0.29
21	87,100	0.21	138	230	0.27

TABLE 24. SUMMARY OF O_2, H_2O, CO, CO_2, AND NO CONCENTRATION IN STACK GAS

Run	Steam Load (lb/hr)	Steam Load by RDF (%)	O_2 (%)	H_2O (%)	CO_2 (%)	CO	NO
						(ppm corrected to 3% O_2)	
1	88,700	0	9.2	5.9	7.6	85	-
2	-	-	-	-	-	-	-
3	110,000	0	8.6	5.6	8.4	80	-
4	107,700	0	8.0	6.6	8.8	85	-
5	99,300	0	8.0	-	8.1	-	-
6	98,700	0	7.8	8.5	9.2	-	-
7	100,000	0	8.6	6.4	9.3	-	-
8	78,200	0	9.0	4.9	8.5	-	-
9	78,000	23	10.0	8.3	8.1	-	-
10	84,800	12	11.0	4.6	6.8	120	320
11	102,100	30	9.0	7.1	8.5	105	320
12	100,000	45	9.0	7.9	10.0	180	280
13	98,600	37	8.9	6.6	10.2	-	-
14	94,000	48	10.0	7.0	8.9	-	-
15	73,400	30	11.1	5.7	8.2	-	-
16	86,500	48	10.1	6.8	7.7	-	-
17	98,800	29	9.3	7.6	8.9	-	-
18	98,800	27	8.9	7.7	8.8	-	-
19	89,700	16	9.0	5.1	9.5	90	295
20	99,100	0	8.1	6.6	10.3	-	-
21	87,100	20	11.4	5.8	8.1	133	315

The coal only tests were 95 ppm CO while the coal plus RDF tests averaged 125 ppm CO.

The nitrogen oxide concentrations in the stack gas, summarized in Table 24, were about 300 ppm (corrected to 3% oxygen). This translates to 0.3 lb NO/10^6 Btu. No trend with percent RDF is apparent from the data. Nitrogen oxide is formed from atmospheric nitrogen and fuel-bound nitrogen. Nitrogen in the coal averaged 1.4% (as received), while nitrogen in the RDF averaged 0.42%. If only the fuel-bound nitrogen were converted to NO the emissions would have been 1.7 lb NO/10^6 Btu for coal only and 1.1 lb NO/10^6 Btu for RDF only. Hence little of the fuel-bound NO is converted. The measured NO emissions are considered to be low.

Trace and Minor Element Analyses of Fuels and Ash

One of the concerns that arises when RDF is used as a supplementary fuel in coal fired boilers is the possibility of increased atmospheric emissions of potentially hazardous trace elements. Landfilled ash from RDF and coal fired boilers may also increase the chance of trace element contamination of ground and surface waters through leaching.

In Table 25 a summary of the elemental analyses of fuels and ashes for coal only and coal plus RDF is presented. The table shows that RDF appears to be richer than coal on the average in 36 of the 63 elements measured. The evidence is not very strong either way for approximately 32 of the elements because of large variations in concentrations, and because so many of the concentrations were at or below the detection limits.

Twelve of the elements in Table 25 are of possible concern from either water pollution or air pollution points of view [18,19,20]. These are silver (Ag), arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), mer-

TABLE 25. ELEMENTAL ANALYSES OF FUELS AND ASH
(Conc. in ppm unless otherwise noted)

			Bottom Ash		Economizer Ash		Cyclone Ash		FLy Ash	
Element	Coal	RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF
Ag	<0.4	<0.5	<1.3	<1.3	<1.0	<0.8	<0.9	<1.3	<12	12
Al(%)	0.97	0.96	9.63	9.12	5.78	4.74	5.80	6.34	13.83	9.95
As	<5	<1.7	<6	<8	60	80	35	40	345	115
Au	<0.001	0.009	0.016	0.010	0.011	0.031	0.012	0.069	0.030	0.080
Ba	< 26	130	720	660	340	820	420	730	620	1270
Br	16	< 60	< 30	< 50	< 25	< 80	< 25	< 90	< 160	< 170
Ca(%)	<0.10	<0.79	<0.24	<0.77	0.31	2.44	<0.25	<2.01	4.64	<2.41
Cd	1.2	8	5	6	5	7	< 3	15	55	360
Ce	14	5.3	300	160	150	55	140	70	110	85
Cl	2250	6760	<110	<170	<100	<260	<90	<400	<740	<3200
Co	4	2.5	45	40	30	20	30	25	75	30
Cr	12	50	170	180	100	185	105	210	345	350
Cs	<1.1	<6	<14	<15	<16	<50	<40	<70	<90	<80
Cu	<50	<440	<170	<340	<140	<270	<130	<280	<1230	<2670
Dy	8	<1.5	22	18	15	6	13	<11	-	20
Er	<2	<13	30	<40	<28	<75	<35	<90	-	<100
Eu	<0.2	<0.06	8	4	4	1.6	4.2	1.7	1.6	<2
Fe(%)	1.6	0.25	21.6	18.3	15.5	7.13	15.09	8.19	4.53	1.60
Ga	<3	<12	<20	<55	<15	<85	<30	<90	430	<340
Gd	1.2	<1.2	<390	1750	<800	<1000	<300	<990	-	<7
Ge	<160	<1140	<2340	<3900	<2100	<5800	<2400	<5600	-	<8760
Hf	<65	530	<1000	<1300	<1000	<3000	<1500	<3200	-	<3150
Hg	<0.6	4.4	<1.6	<1.4	<1.2	<0.9	<1.1	<1.1	<5	29
Ho	<0.9	<0.3	8	7	7	3	8	4	4	1.4
I	<5	<10	<14	<20	<10	<30	<11	<34	<74	<50
In	<0.4	<1.1	<1.5	<2.0	<1.2	<3.2	<1.7	<4	23	<19
Ir	<0.001	<0.002	<0.005	<0.005	<0.004	<0.003	<0.003	<0.003	<0.04	<0.03
K(%)	0.17	0.20	1.54	1.53	.78	1.44	0.89	1.38	3.74	3.35
La	7	2.6	130	80	70	30	60	35	40	30
Lu	0.05	<0.009	0.9	0.6	0.5	0.2	0.5	0.3	0.6	0.2
Mg(%)	0.032	0.098	0.28	0.34	0.20	0.34	0.20	0.32	1.57	4.32
Mn	26	320	165	460	135	1260	170	1780	210	340
Mo	<17	<7	<26	<30	<22	<21	<21	<22	295	150
Na(%)	0.020	0.58		0.83	0.11	2.21	0.12	1.39	24.79	10.07
Nd	6	<2	170	90	90	30	85	40	40	35
Ni	<35	<33	<85	<260	<65	<80	<60	<105	<635	<570
Os	<4	<6	40	35	25	10	25	15	<170	<70
Pb	44	320	50	100	85	290	260	650	2560	1.89%
Pr	<90	<20	<250	<125	<200	<100	<240	<140	<220	<120
Pt	<110	<310	<380	<590	<320	<790	<300	<1370	<2010	<1880

(continued)

TABLE 25. (concluded)

			Bottom Ash		Economizer Ash		Cyclone Ash		Fly Ash	
Element	Coal	RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF	Coal Only	Coal +RDF
Rb	‹10	‹3	150	140	65	40	70	55	80	70
Re	‹0.04	<1.8	0.06	<0.10	0.05	‹0.05	0.05	0.08	<160	<15
Ru	‹0.08	‹0.4	1.0	1.4	0.8	1.8	0.5	1.8	1.7	2.0
Sb	‹2	‹10	‹0.9	‹4.5	2.6	‹7	6	‹20	220	800
Sc	2.3	0.8	35	25	20	10	25	15	30	15
Se	2	<0.8	<1.6	<1.9	<1.2	<0.9	1.3	2.5	10	30
Si(%)	<2.1	‹4.6	<6.60	<8.77	3.95	<10.50	<4.69	13.10	-	-
Sm	4	0.4	90	35	50	15	60	15	10	‹7
Sn(%)	<0.19	<0.22	<0.52	<0.69	<0.39	<0.43	<0.34	<0.41	<4.67	<5.11
Sr	40	‹65	190	<250	<210	215	240	‹185	910	‹535
Ta	<0.09	‹0.2	2.2	1.0	1.0	0.5	1.2	1.2	<5	<3
Tb	0.4	‹0.3	11	6	6	2	5.3	2.4	<6	<4
Te	<2	<1.5	18	20	10	9	12	12	75	‹30
Th	1.3	1.0	22	17	11	7	11	10	12	12
Ti(%)	0.059	0.206	0.48	0.55	0.28	0.61	0.39	0.86	0.70	1.31
Tm	<0.4	<0.2	<0.5	<0.4	<0.4	<1.1	<0.3	<1.5	<4	<4
U	2.4	0.3	25	30	15	10	15	15	45	20
V	30	‹6	235	260	170	115	200	150	830	210
W	‹1.6	‹9	<20	<30	<16	<50	<16	<45	370	80
Yb	0.5	0.12	10	6	5	2	5	3	5	2
Zn	<16	280	<17	<130	<15	75	<15	140	0.29%	1.71%
Zr	<60	<200	820	530	520	400	460	‹740	5670	<18400

Note: Coal: average of 10 samples

RDF: average of 11 samples

Ash: coal only; average of runs 6 and 8 for bottom ash, economizer ash; and cyclone ash; run 20 for fly ash coal + RDF; average of runs 9, 11, 12, 16 and 18 for bottom ash, economizer ash, and cyclone ash, with average RDF heat input of 35% and average RDF mass input of 56%; average of runs 15, 16, 18 and 19 for fly ash, with average RDF heat input of 30% and average RDF mass input of 47%.

< all samples reported as <. i.e. below detection limit

‹ at least one sample above detection limit cury (Hg), manganese (Mn), lead (Pb), antimony (Sb), selenium (Se), and zinc (Zn). The concentrations of these elements in the individual samples of coal and RDF are given in Tables 26 and 27. RDF has a higher concentration of Ba, Cd, Cr, Cu, Hg, Mn, Pb, and Zn, while coal is higher in As and Se. Silver and antimony appear to be higher in RDF as well, but the data is not conclusive because of the detection limits.

Tables 28 through 31 give the concentrations of the twelve trace elements of special concern for individual samples of bottom ash, economizer ash, cyclone ash and fly ash respectively. Runs 6, 8, and 20 were the coal only tests. There is generally a trend of increasing concentration of most of these elements in the ashes with increasing percent RDF heat input.

In general, the concentration of an element in any ash increased with increasing RDF replacement, if RDF has a higher concentration than coal for that element, and vice versa. The most dramatic changes in concentration of certain elements were observed in the fly ash (particulate emissions). This is especially true for elements that are easily volatilized or have a large difference in concentration in coal and RDF.

Fly ash concentrations of the 12 elements of possible concern shown in Table 31 indicate that lead and zinc have the highest levels. A mass balance indicates that most of the lead and zinc are contained in the fly ash rather than in the bottom ash, economizer or cyclone ash, or as gaseous emissions. Lead and zinc emissions are approximately 1 lb/hr when co-firing coal and RDF, which is an increase of 5 to 10 times over burning coal only. The other elements in Table 31 are distributed among the bottom ash, economizer ash, cyclone ash and fly ash, with the exception of mercury. A mass balance of mercury indicates that 90% of the mercury is unaccounted for and hence was emitted as a gas. Stack sampling failed to recover mercury above the detection limit, however,

TABLE 26. INDIVIDUAL TRACE ELEMENT ANALYSES OF COAL (ppm)

Element	RUN												
	6	8	9	10	11	12	15	16	18	19	Mean	Std. dev.	C.V.%
Ag	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.4	-	-
As	2.6	8.0	2.8	2.8	8.1	8.6	2.7	5.3	5.4	6.6	5.3	-	-
Ba	30	40	36	23	47	49	45	16	84	61	43	-	-
Cd	0.8	-	-	-	0.7	0.9	-	-	1.4	1.3	1.0	0.3	30.5
Cr	12	9	13	8	9	11	13	14	19	14	12	3	26.4
Cu	36	62	65	63	54	64	37	23	444	39	49	-	-
Hg	0.9	0.6	0.5	0.4	0.8	0.7	0.4	0.4	0.5	0.5	0.6	-	-
Mn	11	29	23	25	12	33	24	26	41	35	26	9	36.4
Pb	49	-	-	-	47	31	-	-	42	49	44	8	17.4
Sb	2.1	0.1	-.2	-.2	0.2	0.2	2.7	6.0	5.3	1.8	2	-	-
Se	1.6	0.7	2.2	0.6	1.4	1.3	2.9	2.5	4.0	5.0	2	1	64.2
Zn	5	6	5	6	7	6	68	23	10	26	16	-	-

TABLE 27. INDIVIDUAL TRACE ELEMENT ANALYSES OF RDF (ppm)

	RUN													
Element	9	10	11	12	13	14	15	16	17	18	19	Mean	Std. dev.	C.V.%
Ag	0.4	0.6	0.2	0.3	0.5	0.4	0.4	0.5	9.0	0.8	0.4	1	-	-
As	2.5	1.0	2.6	4.7	0.5	0.3	0.4	0.8	2.2	2.3	1.7	2	-	-
Ba	104	170	150	146	75	164	248	123	97	110	157	130	30	23.7
Cd	12.6	8.6	4.9	3.8	-	-	8.1	7.9	6.4	8.4	5.0	7	3	36.2
Cr	51	53	51	42	37	37	40	123	44	42	47	50	20	47.2
Cu	187	80	343	98	2383	75	43	165	741	164	104	400	-	-
Hg	5.4	4.0	1.6	5.7	1.9	1.8	0.9	2.2	16.8	5.8	2.0	4	4	103
Mn	533	478	308	340	175	217	242	323	310	327	310	300	100	34.9
Pb	183	375	481	239	-	-	648	411	155	187	217	320	170	52.2
Sb	15.4	13.7	21.5	19.5	3.8	10.5	7.1	2.9	12.3	2.2	2.7	10	-	-
Se	1.0	0.8	0.8	0.8	0.8	0.7	0.9	0.6	1.1	0.7	0.7	0.8	-	-
Zn	311	474	297	117	167	273	244	472	313	205	219	280	110	40.1

TABLE 28. INDIVIDUAL TRACE ELEMENT ANALYSES OF BOTTOM ASH (ppm)

Run		6	8	10	9	18	11	12	16
% RDF, heat input basis		0	0	11.5	23.1	27.1	29.5	45.0	48.0
% RDF, mass input basis		0	0	27.4	46.1	45.1	55.7	68.4	66.0
Elements	Ag	<1.4	<1.2	<1.2	<1.2	<1.7	<1.3	<1.0	<1.3
	As	< 6	< 5	< 5	< 6	5	< 5	< 5	15
	Ba	840	600	565	590	750	720	670	580
	Cd	5	4	-	-	5	7	-	6
	Cr	180	160	135	165	215	180	170	180
	Cu	<190	<150	<180	<340	480	<230	<260	370
	Hg	<1.7	<1.4	<1.2	<1.4	<1.7	<1.4	<1.2	<1.5
	Mn	160	170	270	350	620	310	460	560
	Pb	35	65	-	-	75	55	115	165
	Sb	≤0.7	1.0	0.4	0.4	<3.3	3.4	12.6	<3.0
	Se	<1.7	<1.4	<1.3	1.3	<4.2	<1.5	0.8	<1.7
	Zn	< 18	< 15	< 14	< 15	<350	< 17	< 14	<230

TABLE 29. INDIVIDUAL TRACE ELEMENT ANALYSES OF ECONOMIZER ASH (ppm)

Run		6	8	10	9	18	11	12	16
% RDF heat input basis		0	0	11.5	23.1	27.1	29.5	45.0	48.0
% RDF mass input basis		0	0	27.4	46.1	45.1	55.7	68.4	66.0
Elements	Ag	<1.1	<0.9	<0.8	<0.6	<1.0	<0.7	<0.7	<0.9
	As	100	20	45	10	15	25	65	270
	Ba	360	320	310	650	990	560	790	1120
	Cd	5	-	-	-	7	3	7	9
	Cr	115	90	100	190	195	135	165	245
	Cu	<140	<130	<160	<310	140	<270	<330	<280
	Hg	<1.3	<1.0	<0.9	<0.7	<1.2	<0.9	<0.9	<0.6
	Mn	100	170	490	1560	1130	800	1140	1660
	Pb	85	-	-	-	220	235	215	475
	Sb	3.1	2.1	<0.3	6.6	<4.1	6.6	9.9	<8.1
	Se	<1.3	<1.0	<1.0	<0.7	<0.9	<0.8	1.0	<0.9
	Zn	< 15	< 10	< 10	< 10	125	< 11	35	65

TABLE 30. INDIVIDUAL TRACE ELEMENT ANALYSES OF CYCLONE ASH (ppm)

Run		6	8	10	9	18	11	12	16
% RDF heat input basis		0	0	11.5	23.1	27.1	29.5	45.0	48.0
% RDF mass input basis		0	0	27.4	46.1	45.1	55.7	68.4	66.0
Elements	Ag	<1.0	<0.8	<0.9	<0.6	<1.1	<0.8	<0.8	3.1
	As	40	30	50	30	50	35	25	50
	Ba	470	360	540	510	760	620	910	870
	Cd	< 3	-	-	-	18	10	14	17
	Cr	115	95	150	190	200	175	255	235
	Cu	<130	<120	<250	<340	<230	<270	<390	190
	Hg	<1.2	<1.0	<1.1	<0.9	<0.8	<1.0	1.9	<0.9
	Mn	165	180	1440	2410	1330	1250	2480	1440
	Pb	260	-	-	-	635	540	550	860
	Sb	6	5	11	13	25	19	31	< 14
	Se	0.9	1.7	2.1	2.9	0.9	1.1	3.0	4.6
	Zn	< 15	< 10	155	110	115	20	170	290

TABLE 31. INDIVIDUAL TRACE ELEMENT ANALYSES OF FLY ASH (ppm)

Run		20	19	18	15	16
% RDF, heat input basis		0	16.4	27.1	30.4	48.0
% RDF, mass input basis		0	30.4	45.1	48.4	66.0
Elements	Ag	<12	<10	7	11	17
	As	345	70	185	125	85
	Ba	620	1960	1030	890	1180
	Cd	55	165	350	350	590
	Cr	345	265	295	380	455
	Cu	1230	<5290	<2150	<1230	1990
	Hg	<5	13	15	29	59
	Mn	210	55	430	360	510
	Pb	2560	18400	11500	28200	17600
	Sb	220	570	710	880	1050
	Se	10	25	15	55	25
	Zn	2900	17510	17780	13400	19830

mercury levels in the fuel are low in any event.

To determine the distribution of the trace elements among the four ash types, the ratio of the concentration of each element in each ash type to the concentration of aluminum in that ash was compared to the corresponding ratio for the fuel. Aluminum was used as a reference element because of its nonvolatile nature. An enrichment factor, EF_{ij}, of each element, i, in each ash, j, relative to the input was calculated from,

$$EF_{ij} = \frac{C_{ij}/C_{alj}}{(fC_i/C_{al})_{coal} + (fC_i/C_{al})_{RDF}}$$

Where C is the concentration, al refers to aluminum, and f is the mass input fraction of coal or RDF.

The value of the enrichment factor indicated whether an element is enriched ($E_{ij} > 1.0$), nonenriched ($E_{ij} = 1.0$), or depleted ($E_{ij} < 1.0$) in an ash relative to aluminum and relative to the total input.

In Table 32 the enrichment factors for selected elements in the various ashes are given. Generally, the boiling point of the elemental oxide determines the ranking of the enrichment factors in a boiler[21]. Oxides with low boiling points tend to be volatilized in the combustion process. As the hot, flowing combustion gases and suspended particles are cooled as they exit the boiler, the volatilized elements adsorb and condense on surfaces of particles. Because the finer ash particles have a higher surface area per unit mass than coarser particles, they will contain relatively higher concentrations of the volatilized elements[21]. This general relationship was also found in this project. Oxides with low boiling points tend to be enriched in the fly ash. Some of the most volatile elements (Hg, Se), however, do not completely condense and are partially emitted in the vapor state.

TABLE 32. TRACE ELEMENT ENRICHMENT FACTORS FOR ASHES

	Enrichment Factor
Bottom ash	
Ag, As, Cd, Cu, Hg, K, Mg, Mn, Na, Pb, Sb, Se, Ti, Zn	<1
Ba, Ce, Co, Cr, Fe, La, Lu, Nd, Os, Sc, U, V	1-3
Economizer ash	
Ag, (As), Cd, Cu, Hg, Os, Pb, Sb, Se, Zn	<1
Ba, Ce, Co, Cr, Fe, K, La, Lu, Mg, Mn, Na, Nd, Sc, Ti, U, V	1-3
Cyclone ash	
Ag, Cd, Cu, Hg, Os, Pb, Sb, Se, Zn	<1
As, Ba, Ce, Co, Cr, Fe, K, La, Lu, Mg, Mn, Na, Nd, Sc, Ti, U, V	1-3
Fly ash	
Ce, Co, Fe, La, Lu, Mn, Nd, Sc, Ti, V	<1
Ag, Ba, Cr, Cu, Hg, K, Os, Se, U	1-3
As, Mg	3-7
Cd, Na, Pb, Sb, Zn	>7

GENERAL OBSERVATIONS - BOILER OPERATION AND PERFORMANCE

The following observations were made by members of the grant research team over the course of the project.

Boiler Control

The boiler control system is designed to control the feed rate of the primary fuel and air flow in response to varying steam demand. A pressure sensor in the boiler master control detects changes in steam flow. As temperature in the furnace increases, steam flow increases. The boiler master will change the stoker drive and cut back on coal feed as needed. The forced draft fan tracks output of steam flow and adjusts excess air to desired levels. Above 50% load, the forced draft fan output is almost a linear relationship to coal feed but may vary below this level.

An independent and constant refuse fuel feed system allowed the existing fuel control systems to respond to load changes just as if the boilers were fired on 100% primary fuel. RDF feed was metered into the boiler through separate feed chutes. Variable drive mechanically adjustable augers, in the bottom of a live bottom RDF feed bin, regulate the RDF feed. A mechanical adjustment on the auger drive allowed feed rate adjustments over the desired range of one to eight tons per hour.

During the test program, load on the boiler was typically brought up to about 50,000 lb steam/hr using coal. Then refuse was introduced into the system slowly, increasing load up to the desired operating level over a ten to fifteen minute period. In order to achieve the maximum RDF feed rate used during the tests, the feed rate was increased in increments of one to two tons/hr over a period of about fifteen minutes.

A new 100 Hp blower and additional overfire air piping were added during retrofit of the Oscar Mayer boiler. Two air ducts were connected to the fan outlet. One provided constant air flow for RDF sweep and distribution air. The other provided overfire air at two levels above the grate in the rear wall and at two levels above the grate in the front wall as shown in Figure 23. A high pressure automatic damper in the second line operated in step with the main air supply by mechanical linkage. The refuse feed system and the coal feeders were interlocked to shut down when the overfire air fan shut down.

Boiler Response

Boiler control and response was not compromised by co-firing RDF. During most tests, the steam load was easily held within ±4.5% of the desired steam load. Minor exceptions included slippage of the RDF feed conveyor during early practice runs and running out of RDF.

The RDF was found to be more volatile than coal making it necessary to introduce the RDF into the boiler at incremental feed rates to avoid too rapid an increase in steam flow. The volatile nature of RDF is due to the substantial quantity of very light short fiber paper and film plastic which will burn by flash combustion in the air above the grate. About one third of the RDF fuel may fall in this category. The remaining RDF contains a substantial quantity of long fiber paper, high density plastic, wood and textiles which will drop to the hot bed of material on the grate, and will also burn faster than coal.

Clinker Formation

Some clinker formation was observed during the early part of the test program. Assuming good burning conditions are present, clinkering would not be expected with the RDF used. It should be noted that the RDF was finely shredded and most of the glass and metals had been removed. The clinkering which occurred was minor and was ultimately resolved with adjustments in overfire and underfire

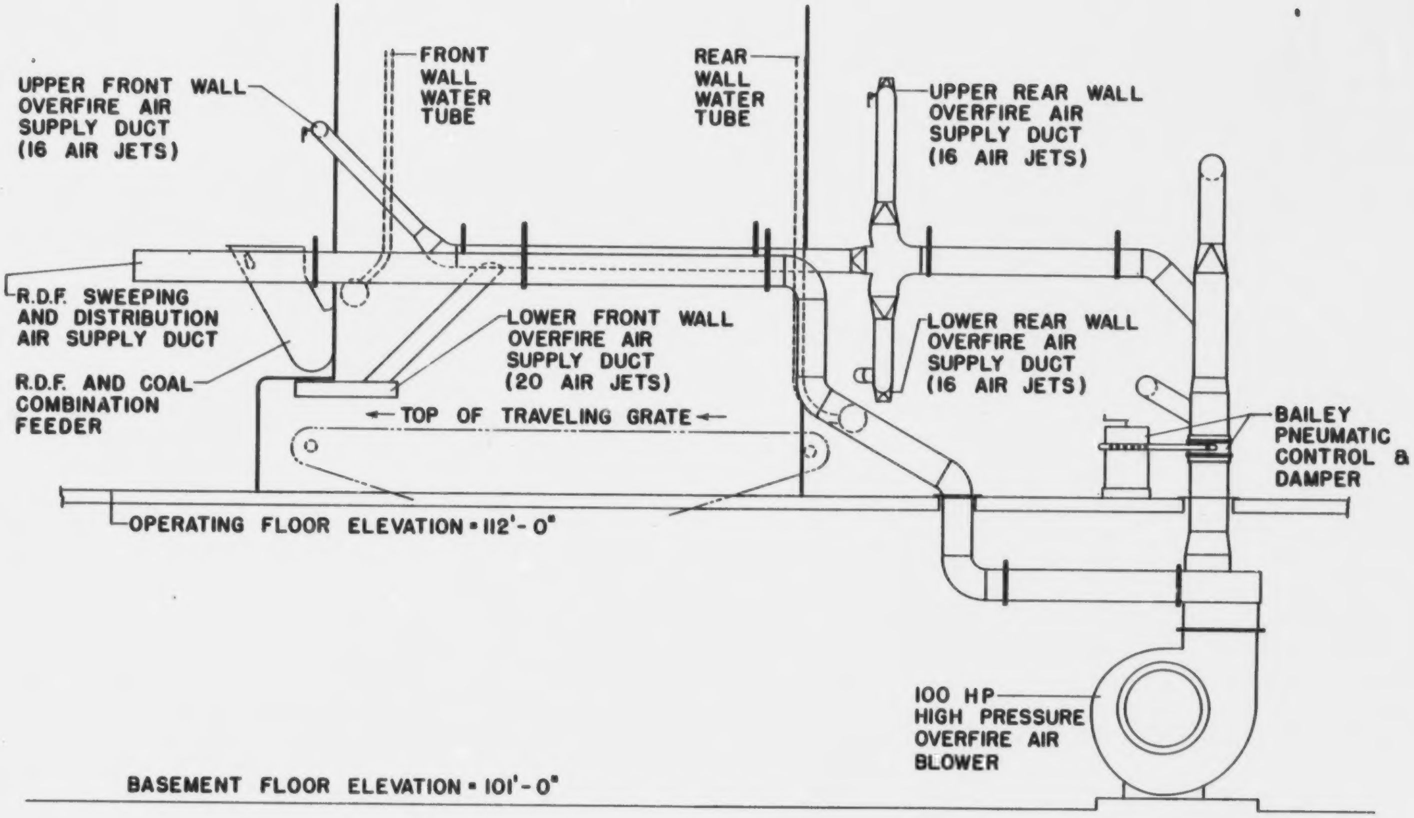
UPPER FRONT WALL OVERFIRE AIR SUPPLY DUCT (16 AIR JETS)
FRONT WALL WATER TUBE
REAR WALL WATER TUBE
UPPER REAR WALL OVERFIRE AIR SUPPLY DUCT (16 AIR JETS)
R.D.F. SWEEPING AND DISTRIBUTION AIR SUPPLY DUCT
LOWER FRONT WALL OVERFIRE AIR SUPPLY DUCT (20 AIR JETS)
LOWER REAR WALL OVERFIRE AIR SUPPLY DUCT (16 AIR JETS)
R.D.F. AND COAL COMBINATION FEEDER
← TOP OF TRAVELING GRATE ←
BAILEY PNEUMATIC CONTROL & DAMPER
OPERATING FLOOR ELEVATION = 112'-0"
100 HP HIGH PRESSURE OVERFIRE AIR BLOWER
BASEMENT FLOOR ELEVATION = 101'-0"

Figure 23. Overfire Air System Boiler No. 5

air distribution and work with RDF distribution to achieve a good even spread of material on the grate.

It was also found that material on the refuse transport conveyor was slightly biased toward one side producing heavier loads to one side of the flow splitter. This was easily corrected at the point of feed to the conveyor. Until the distribution problems were corrected material could be observed mounding in a few places on the grate.

During the last test run, a coarse 4-inch particle size RDF was fired. The fact that no clinkering occurred during this run could be attributed to the work and experienced gained on the finely shredded RDF.

Furnace Wall Deposits

Furnace wall deposits have been relatively light but have occurred on each of the four furnace walls. The deposits appear thickest on the back wall of the furnace around the gas burner openings. The burners were not used during the period of RDF burning, however, cooling air amounting to 30% of the underfire air was passed through the idle burners to prevent overheating. The wall deposits tend to be negligible at the 15-ft elevation above the furnace grate and above the overfire air nozzles.

Periodically throughout the course of the research program, the boiler was taken down and closely inspected. The following figures show several locations in the boiler as they appeared prior to the start of the RDF test program, after firing 180 tons of RDF, and finally after firing 600 tons of RDF at the completion of the project. The figures illustrate that any build-up on the boiler walls and combination feed ports was only slightly more than what had been experienced on coal-only firing and within operating standards acceptable to Oscar Mayer.

Furnace Grates

No significant deterioration of the furnace grates occurred during the test period. Early concerns related to potential hot spots on the grate and possibly inadequate underfire air did not prove to be problems. Close inspection of the grates after a few test runs revealed hairline cracks in two small areas and metal spauling over a few inches of one grate section. However, the grates had not been closely inspected prior to the tests and only a few sections had been replaced in several years. No further grate wear was observed in subsequent inspections.

Smoke Plume Density

During all of the test runs, the smoke plume was visually monitored by operating personnel. The plume color and smoke density during RDF co-firing was judged to be about the same as when burning coal only. The smoke density chart readout indicated an increase in smoke density of about 10% during each of the RDF test runs

Other Observations

Boiler attention by operating personnel was approximately the same when RDF was being burned as when only coal was being fed to the boiler. On a few occasions the bed depth of ash appeared to be high at high RDF feed rates, requiring more frequent observation. However, as experience was gained with the air system and RDF distribution in the furnace, bed depth did not appear to be a problem.

COMPARISON OF TEST RESULTS WITH OTHER TEST DATA

Section 2 lists a number of North American Cities where energy is recovered from municipal solid waste. One third of these towns employ the older European technology of mass burning. The others involve prepared fuel systems, collectively handling less than 1% of the total municipal solid waste generated annually in the United States.

Table 33 and 34 compares the operating conditions and test results of the Oscar Mayer tests with seven other refuse burning installations and the EPA supported demonstration project in St. Louis. There is general agreement between the tests at Oscar Mayer and the performance reported for other locations. These tests indicate:

1. Refuse can be prepared to produce a fuel which can be burned with coal in existing coal-fired boilers.
2. Refuse fuel may supply a high percentage of the heat load in existing spreader-stoker industrial boilers.
3. The control of particulate emissions when burning refuse fuel does appear anymore difficult than when burning coal alone.

TABLE 33. COMPARISON OF OPERATING CONDITIONS AND TEST RESULTS WITH OTHER LOCATIONS

Location	Type of Facility	RDF Feed to Boiler	Boilers Size	Boilers MFG	RDF Particle Size	Per Cent RDF Based on Steam Load	Ash System	Combustion Air	Particulate Controls
Spreader Stoker Operations									
Madison, Wisconsin (Oscar Mayer)	Industrial Spreader Stoker (Coal Burning)	Gravity, six Pneumatic Distributors* Combination Coal RDF Fedders RDF above coal	125,000 lb/hr	CE	3/4" (one 4" test)	0 - 20%	Dry pit pneumatic to silo	Overfire 40% Underfire 60% Excess Air 55%-115%	Multiclone
Ames, Iowa (Ref No. 24 & 25)	Municipal Utility Spreader Stoker (Coal Burning)	2 Pneumatic Lines above Coal Spreaders	#5 95,000 lb/hr #6 125,000 lb/hr	Riley Union Iron	1 1/2"	0 - 50%	Dry Pit Pneumatic to silo	High Excess Air on coal only increasing 17-34% with RDF	Multiclone Multiclone
Columbus, Ohio (Ref No. 26)	Municipal Utility Spreader Stoker (Coal Burning)	Gravity two Pneumatic* at 90 to and above coal Spreaders	150,000 lb/hr	Riley	4 "	0 - 60%	Dry pit pneumatic to silo	INA	Multiclone
Hamilton, Ont. ** (Ref No. 27, 28, & 29)	Municipal Utility Spreader Stoker	Pneumatic* Distributors	105,000 lb/hr (two units)	B & W	2 - 4"	Approx. 100%	Submerged Scraper Belt Conv. to Silo	INA	Electrostatic Precipitator
Akron, Ohio ** (Ref No. 30 & 31)	Municipal Utility Spreader Stoker	Gravity, four Pneumatic* Distributors	126,000 lb/hr (two units)	B & W	2 - 4"	Approx. 100%	Dry pit pneumatic to silo	Overfire 20% Underfire 80%	Electrostatic Precipitator

(continued)

TABLE 33. (concluded)

Location	Type of Facility	RDF Feed to Boiler	Boilers		RDF Particle Size	Per Cent RDF Based on Steam Load	Ash System	Combustion Air	Particulate Controls
			Size	MFG					
Pulvarized Coal Operations									
Madison, Wisconsin (Ref No. 2)	Public Utility Pulverized Coal	2 Pneumatic Lines between middle & lower coal feed lines	425,000 lb/hr 60 MW (two units)	B & W	3/4"	10 - 20%	Dry pit pneumatic to silo	Excess Air	Electrostatic Precipitator
Ames, Iowa (Ref No. 24, 25 & 32)	Municipal Utility Pulverred Coal	Pneumatic to corners above two rows of coal nozzels & to two corners below	360,000 lb/hr 35 MW	CE	1 1/2"	10 - 20%	Wet Bottom with swile	Excess Air 35 - 42%	Electrostatic Precipitator
St. Louis, Mo. (Demonstration Project) (Ref No. 32, 33 & 34)	Public Utility Pulverized Coal	Pneumatic to each corner between 2 upper & 2 lower rows of coal nozzles	125MW	CE	1 1/2"	10 - 20%	Wet Bottom with swile	INA	Electrostatic Precipitator
Milwaukee, Wisconsin (Ref.No. 22)	Public Utility Pulverized Coal	Pneumatic to each corner above 5 rows of coal nozzles	2,000,000 lb/hr - 310MW two units	CE	1 1/2"	10 - 20%	Wet Bottom with swile	3.8% O_2 on coal 5.0% with RDF to retard slag accumulations	Electrostatic Precipitator

* Air Swept Spouts
** Designed to Burn Refuse as 100% of Fuel.

TABLE 34. COMPARISON OF OPERATING CONDITIONS AND TEST RESULTS WITH OTHER LOCATIONS

Location	Method of RDF Preparation	RDF Feed System Performance	Boiler Efficiency	Coal Supply	Sulfur Dioxide	Hydrogen Chloride	Nitrogen Oxide	Particulate Emissions	Slagging	Clinkering
Spreader Stoker Operations										
Madison, Wisconsin (Oscar Mayer)	Flail, Mag. Sep. screen, fine shred air classify	Good-constant feed at uniform depth-good distribution in boiler	Decrease 1% for each 10% of load replaced by RDF	Illinois	Substantial reduction as RDF feed increases	Increase about 50%	No change	No significant change	Minor	Insig.
Ames, Iowa (Ref. No. 24 & 25)	Coarse shred mag. sep. fine shred, air classify	Feed from storage variable problems with control prior to addition of screens.	Decrease 1% for each 20% of load replacement by RDF	Iowa Wyoming	Significant decrease as RDF feed increases	Increased linerally as RDF feed increases	General decrease	No clear trends	Insig.	Insig.
Columbus, Ohio (Ref. No. 26)	Fine shred mag. sep.	Generally good		3% sulfur Ohio	Substantial reduction	Slight increase	No significant change	Inconclusive	Used slagging type coal reduced by better RDF & air distribution	Insig.
Hamilton, Ont. (Ref No. 27, 28 & 29)	Fine shred mag. sep.	Good after by-pass of storage bin	Approx. 76%	- -	Expected low due to high % RDF	Information not available			None	Minor
Akron, Ohio (Ref. No. 30 & 31)	Fine shred, Air classify	Inconsistant, difficulty with control	Approx. 78%	- -	Expected low due high % RDF	Information not available		No tests stack appearance is good	None	Minor

(continued)

TABLE 34. (concluded)

Location	Method of RDF Preparation	RDF Feed System Performance	Boiler Efficiency	Coal Supply	Sulfur Dioxide	Hydrogen Chloride	Nitrogen Oxide	Particulate Emissions	Slagging	Clinkering
Pulverized Coal Operations										
Madison, Wisconsin*** (Ref. No. 2)	Flail, Mag. Sep. Screen, Air Classify	Good-relatively constant	Decrease 1% for each 10% of load replacement by RDF	Illinois Eastern Ky & Wyoming	Reduced	Information not available		No significant change	None	Minor
Ames, Iowa*** (Ref. No. 24, 25, and 32)	Coarse shred, Mag. Sep. Disc Screen, Fine shred, Air Classify	Generally good after modifications and addition of disc screens	Decrease 1% for each 10% of load replaced by RDF	Iowa - Colorado	Significant decrease	Significant increase	General decrease	No clear trends	Slagging on rear wall	Yes - reduced by disc screens & more under fire air
St. Louis, Mo. (Ref No. 32, 33, and 34)	Fine shred, Air Classify	Relatively well-periodic air lock jams & line tears. Must keep light load in storage bin	INA	Illinois	Significant decrease	Increase about 30%	No change	Some increase at high boiler loads	No increase	- - -
Milwaukee, Wisconsin (Ref. No. 22)	Coarse Shred, Air Classify, Fine Shred, Mag. Sep., Disc Screen	Generally good	Significant reduction attributed to low 1.0 fan capacity & slagging	Variable sources or slagging potential coal	No change indicated	Increase 106 lb per 10^6 BTU	15% reduction	Increase	Significant with coal only-increase with RDF	- - -

*** Drop grates were added.

SECTION 5

THE OSCAR MAYER RDF FEED SYSTEM

DESCRIPTION OF THE SYSTEM INSTALLED

The basic operations of the test facility are shown in the facility process flow diagram, Figure 18, and are summarized below.

RDF Receiving and Storage

Refuse-derived-fuel (RDF) prepared at the Madison Area Recovery Center, was delivered by a 75-cubic yard enclosed transfer trailer. The RDF was discharged on a concrete slab in the receiving and storage building. The building is a 36 ft by 48 ft pre-engineered metal building with a ground level concrete slab floor. A rubber tire loader was used to stockpile the incoming RDF against reinforced concrete push walls, and to load the feed bin.

RDF Auger Feed Bin

The RDF auger feed bin is a 4 ft deep by 16 ft long floor mounted bin with two 14-inch diameter by 19.75 ft long augers. Screw flighting is mounted on a 6-inch diameter pipe and the augers are mounted side by side in individual trenches. The receiving side of the bin is 4 ft high for easy access by the loader. The back side of the bin is 8 ft high to control spillage. During operation the bin is loaded to a depth of 4 ft to 5 ft. The RDF discharges beneath an end wall onto the inclined tail section of a slider belt conveyor. The augers are driven by a single 7-1/2 hp Louis Allis motor with a mechanically adjustable variable Allis-speed drive. The auger speed range is 2.6 to 26 RPM.

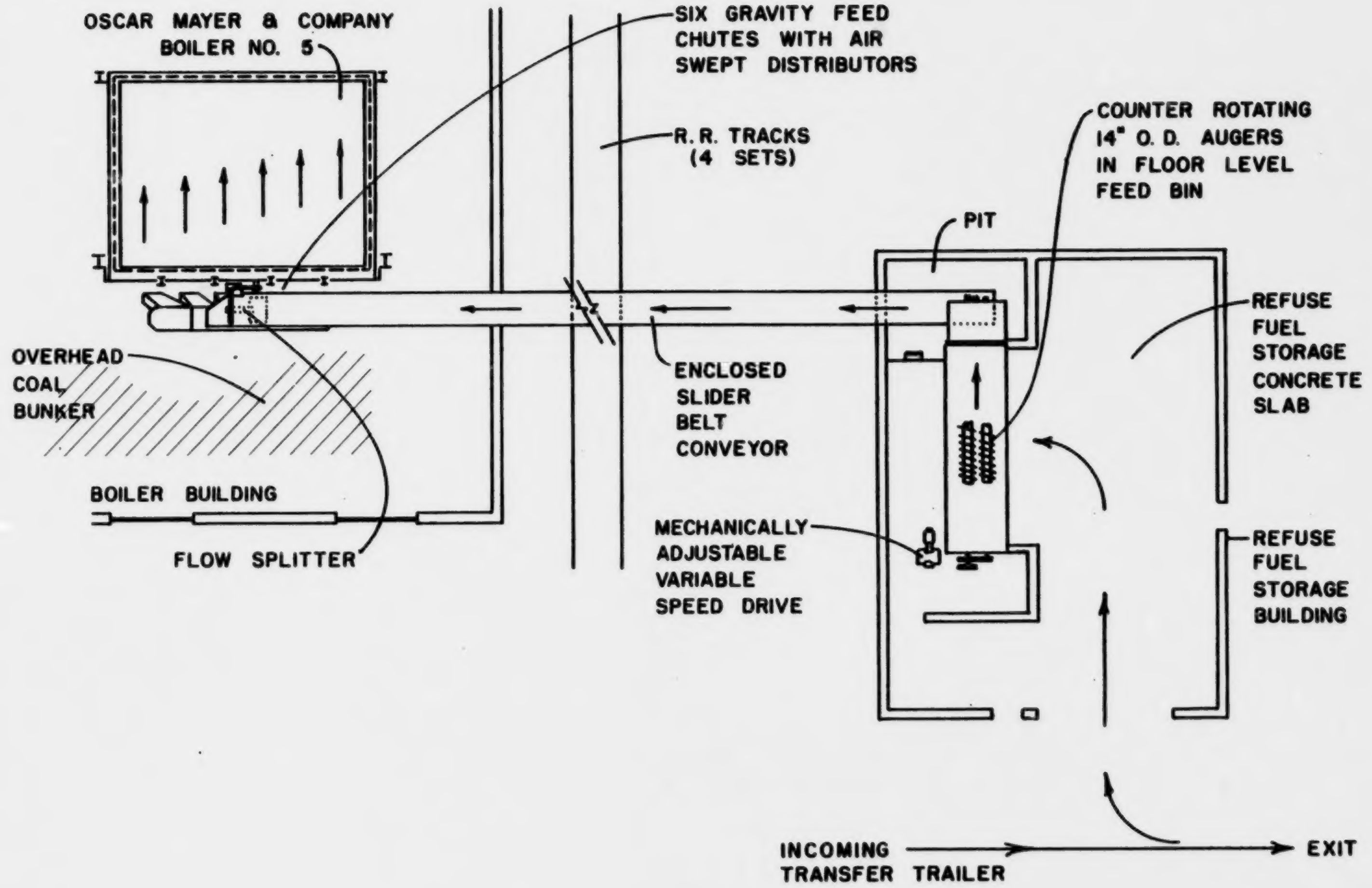
OSCAR MAYER & COMPANY BOILER NO. 5
SIX GRAVITY FEED CHUTES WITH AIR SWEPT DISTRIBUTORS
R.R. TRACKS (4 SETS)
COUNTER ROTATING 14" O.D. AUGERS IN FLOOR LEVEL FEED BIN
PIT
REFUSE FUEL STORAGE CONCRETE SLAB
OVERHEAD COAL BUNKER
ENCLOSED SLIDER BELT CONVEYOR
BOILER BUILDING
FLOW SPLITTER
MECHANICALLY ADJUSTABLE VARIABLE SPEED DRIVE
REFUSE FUEL STORAGE BUILDING
INCOMING TRANSFER TRAILER
EXIT

Figure 18. Oscar Mayer & Company RDF Receiving and Feed Facility

The augers were supplied by Wolf and Associates, Incorporated of Fridley, Minnesota.

Material Conveying

The conveyor is a 2 ft wide by 125.3 ft long slider belt, as illustrated in Figure 18. The conveyor receives the RDF, discharged from the RDF auger feed bin, in a 5 ft deep receiving pit. The conveyor carries the RDF out of the receiving pit at an incline of 36° for the first 48 ft in order to clear a series of railroad tracks, then runs horizontally for an additional 77.3 ft to the RDF flow splitter inside the boiler building.

The slider belt is housed in a fully enclosed structure approximately 2 ft square. An access walkway parallels the full length of the conveyor on one side and two center supports allow the conveyor to span between the RDF receiving and feed facility and the boiler building. The carrying side of the slider belt is accessible through removable top plates the full length of the conveyor. The return side of the belt is accessible through the hinged side access panels the full length of the conveyor.

A clear plastic viewing panel is located at the bend portion of the conveyor and at the discharge end of the conveyor to provide an opportunity for inspection of the belt and material on the belt. The receiving end of the belt, inside the refuse fuel building, is uncovered and also provides an opportunity for inspection.

The conveyor is driven by a 7½ hp motor and has a gravity pulley near the head pulley on the under carriage return side. The gravity pulley is fixed to a pipe sleeve structure which can float in a vertical plane and can be loaded with weights as needed to maintain the desired belt tension on the return side, as shown in Figure 19.

The conveyor has 2 inch high cleats spaced 1 ft on center, separated in the middle to accomodate belt tracking on the return side.

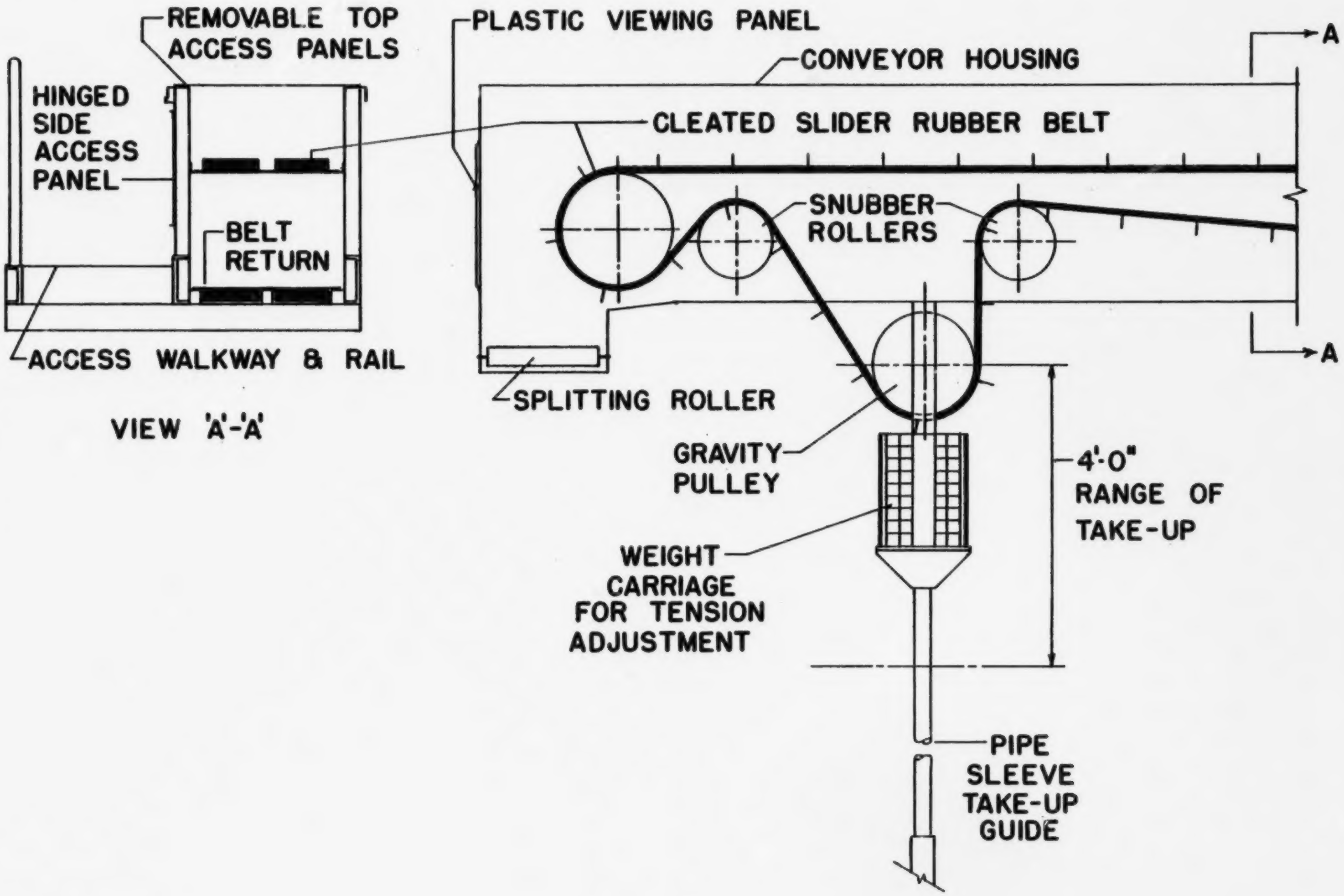
REMOVABLE TOP ACCESS PANELS
HINGED SIDE ACCESS PANEL
BELT RETURN
ACCESS WALKWAY & RAIL
VIEW 'A'-'A'
PLASTIC VIEWING PANEL
CONVEYOR HOUSING
CLEATED SLIDER RUBBER BELT
SNUBBER ROLLERS
A
A
SPLITTING ROLLER
GRAVITY PULLEY
WEIGHT CARRIAGE FOR TENSION ADJUSTMENT
4'-0" RANGE OF TAKE-UP
PIPE SLEEVE TAKE-UP GUIDE

Figure 19. Slider Belt Conveyor Gravity Pulley

The conveyor was supplied by The Heil Company of Milwaukee, Wisconsin.

Flow Splitting and Feed into the Boiler

RDF is conveyed in a straight line, in the fully enclosed conveyor described above, across a series of railroad tracks into the boiler building. The RDF is conveyed along the front wall of boiler no. 5, between the boiler and the parabolic bottom of the coal bin. The RDF is discharged from the conveyor at the center of the front wall of the boiler.

At this point, the material discharges vertically across a rotating splitting roller located inline and beneath the conveyor head pulley. The material is split into two streams and falls into two sloping pant-leg type chutes, which discharge into swinging spouts. Each of the swinging spouts feeds a set of three sloping chutes which have rotating cleaning rollers over the common intersection points at the top, as shown in Figure 20. The six feed chutes drop the RDF to feed openings in the boiler, immediately above the six combination coal feeders, where an air supply blows and spreads the material, in a windswept fashion, across the grate of the spreader-stoker furnace.

The two swinging spouts are powered by a single 3/4 hp motor with a common linkage bar between the spouts, connected by pins to swing arms on each of the spouts, one of which is connected by pins to a slow rotating arm on the drive motor. The rotating cleaning rollers, over the six feed chutes, have a chain and sprocket drive and are powered by a single 1 hp motor which drives a common chain across the roller sprockets.

The six airswept entries into the furnace are through transitions which are an intergal part of the combination coal feeder. The coal feeder, with refuse fuel transition above, is referred to by the manufacturer as a Combination Feeder. Each of the airswept entries into the furnace is supplied by a common air

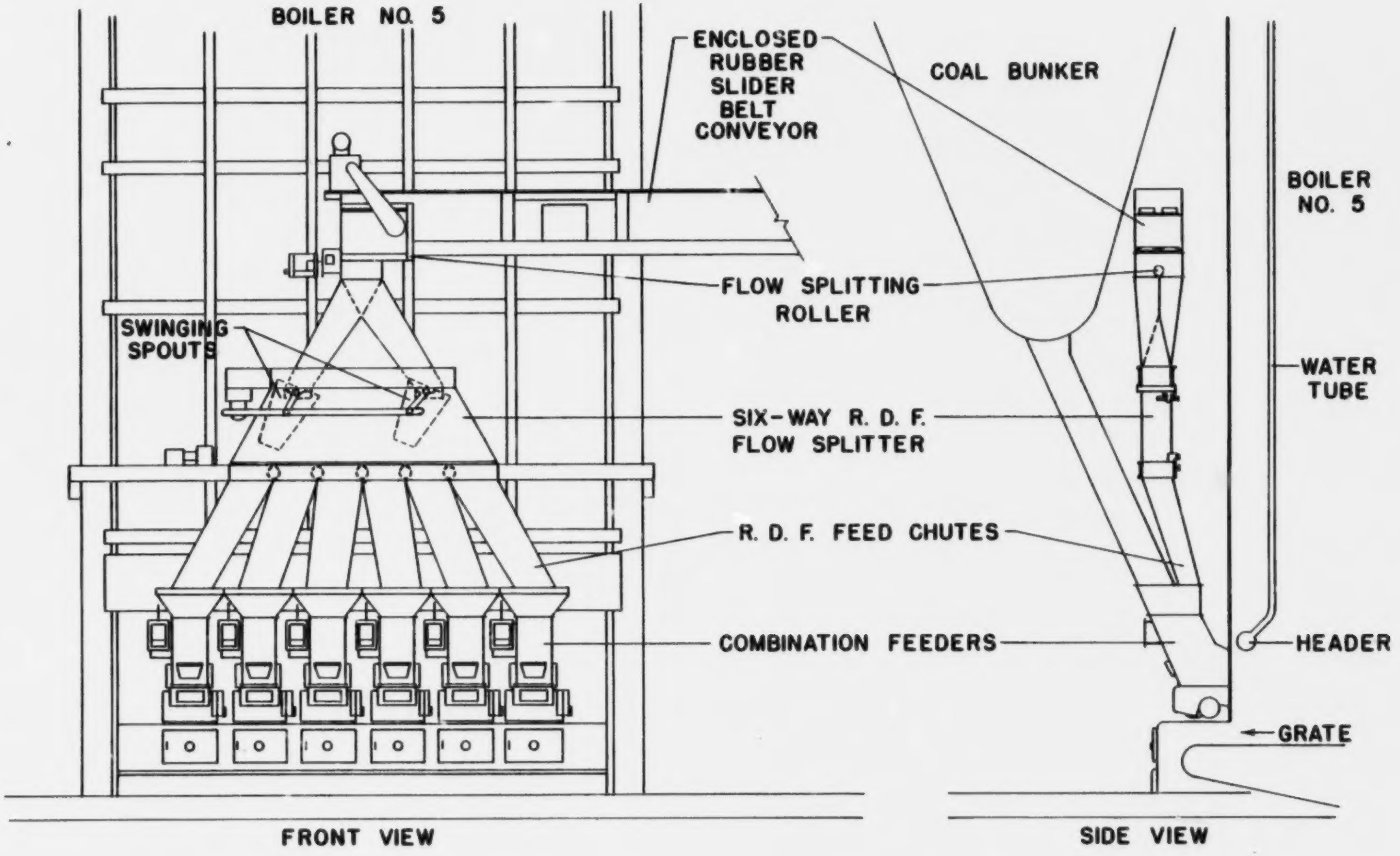
BOILER NO. 5
ENCLOSED RUBBER SLIDER BELT CONVEYOR
COAL BUNKER
BOILER NO. 5
FLOW SPLITTING ROLLER
SWINGING SPOUTS
WATER TUBE
SIX-WAY R. D. F. FLOW SPLITTER
R. D. F. FEED CHUTES
COMBINATION FEEDERS
HEADER
GRATE
FRONT VIEW
SIDE VIEW

Figure 20. RDF Flow Splitting and Feed into the Boiler

header from the overfire air fan. Each has a motorized air damper in the breeching between the air supply and the air chamber which can be adjusted to accomodate an even spread of material across the furnace, as shown in Figure 21.

The swinging spout assembly was supplied by Universal Welding Company of Waukesha, Wisconsin and is shown in Figure 20.

RDF and Coal Combination Feeders

The RDF falls through the 18-inch wide RDF chute portion of the combination hopper and feeder, shown in Figure 22. Coal is flowing in parallel with RDF through the combination hopper. The coal flows onto the adjustable spilling plate,then falls onto the rotor where it is fed and spread on the boiler grate. The rotor is driven by the boiler's existing lineshaft and drive mechanism.

The RDF falls past the counterweighted balanced damper and is airswept into the boiler and onto the grate. Adjusting the air proportioning damper, regulates the air split between sweeping air and distribution air. Regulating this air split controls the throw and spread of the RDF on the grate and assures an even distribution of RDF throughout the boiler.

Each of the six combination feeders was supplied with a mounting plate, air-cooled tuyere arrangement, and a water cooled feed throat. The coal feed portion of the combination feeder is identical to the existing roto-grate coal feeders which they replaced. The combination feeder installation, at Oscar Mayer, is the first time that this feeder has been used to feed coal and RDF in combination.

The combination coal and RDF feeders were supplied by Detroit Stoker Company of Monroe, Michigan.

Overfire Air System

To facilitate the burning of RDF in the Oscar Mayer boiler, the existing high pressure overfire air blower with a 20 hp motor and an existing low pressure overfire air blower with a 7-1/2 hp motor were removed. They were re-

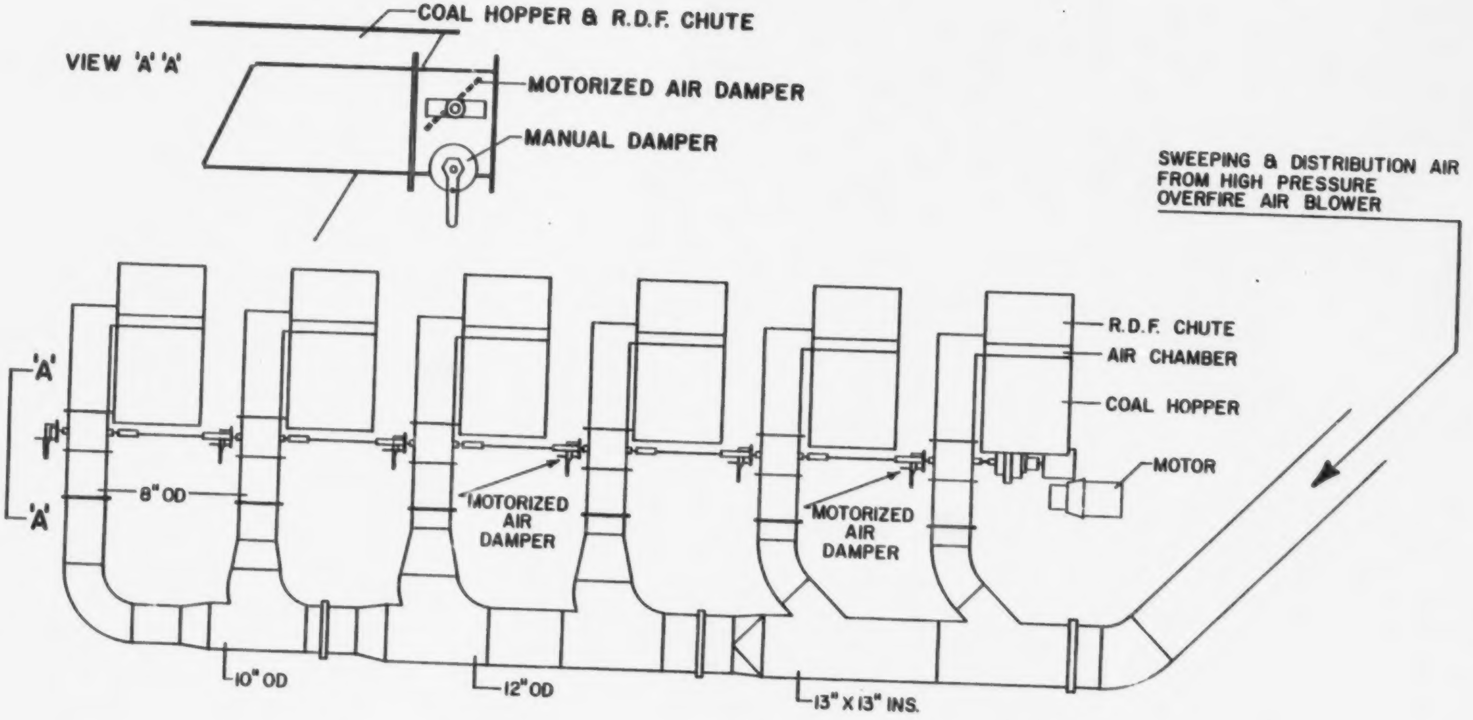
VIEW 'A' 'A'
COAL HOPPER & R.D.F. CHUTE
MOTORIZED AIR DAMPER
MANUAL DAMPER
SWEEPING & DISTRIBUTION AIR FROM HIGH PRESSURE OVERFIRE AIR BLOWER
'A'
'A'
R.D.F. CHUTE
AIR CHAMBER
COAL HOPPER
MOTOR
8" OD
MOTORIZED AIR DAMPER
MOTORIZED AIR DAMPER
10" OD
12" OD
13" X 13" INS.

Figure 21. RDF Sweeping and Distribution Air Plan View

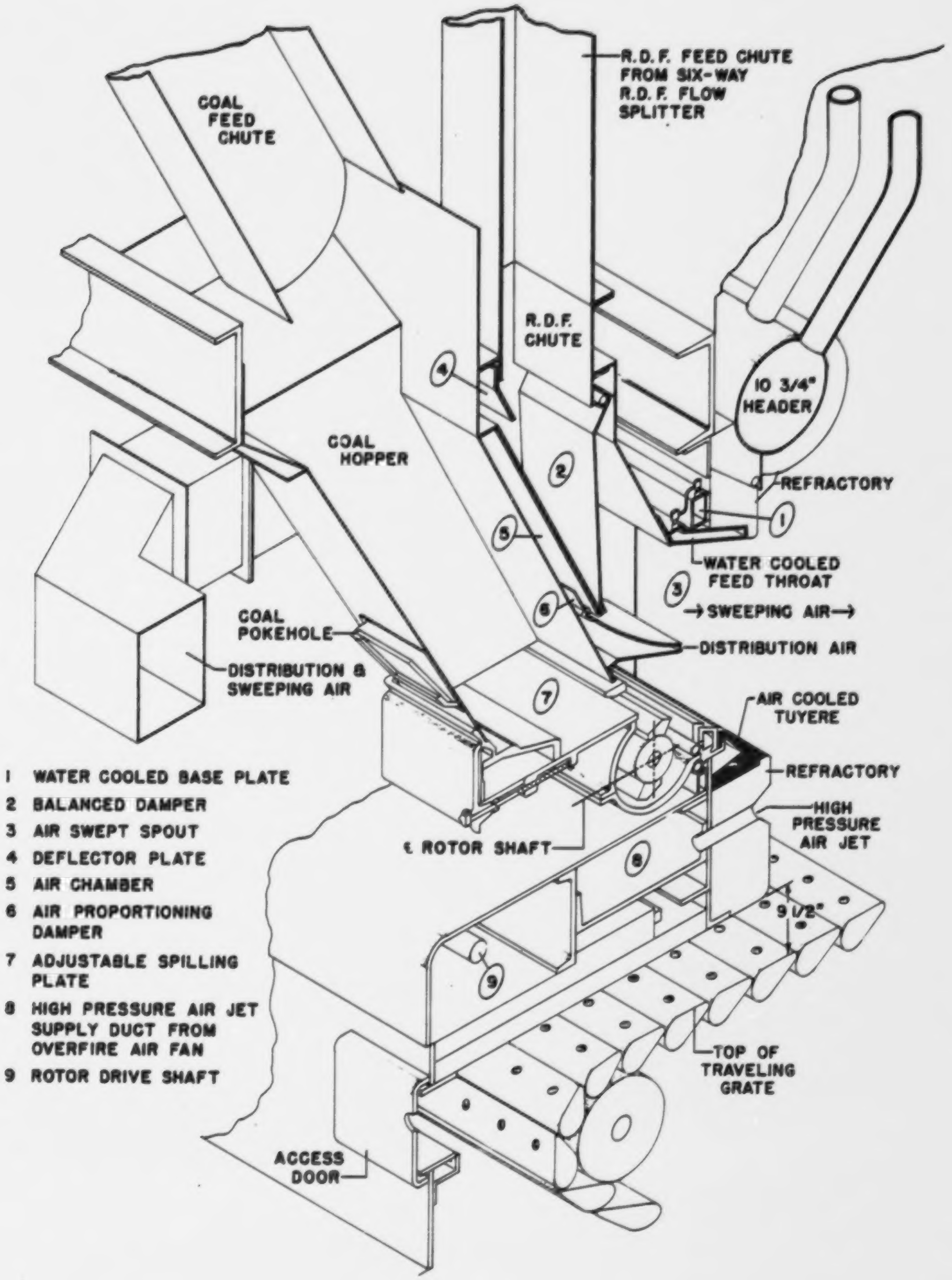
COAL FEED CHUTE
R.D.F. FEED CHUTE FROM SIX-WAY R.D.F. FLOW SPLITTER
R.D.F. CHUTE
10 3/4" HEADER
COAL HOPPER
REFRACTORY
WATER COOLED FEED THROAT
→SWEEPING AIR→
COAL POKEHOLE
DISTRIBUTION AIR
DISTRIBUTION & SWEEPING AIR
AIR COOLED TUYERE
REFRACTORY
HIGH PRESSURE AIR JET
℄ ROTOR SHAFT
9 1/2"
TOP OF TRAVELING GRATE
ACCESS DOOR
1
2
3
4
5
6
7
8
9
1 WATER COOLED BASE PLATE
2 BALANCED DAMPER
3 AIR SWEPT SPOUT
4 DEFLECTOR PLATE
5 AIR CHAMBER
6 AIR PROPORTIONING DAMPER
7 ADJUSTABLE SPILLING PLATE
8 HIGH PRESSURE AIR JET SUPPLY DUCT FROM OVERFIRE AIR FAN
9 ROTOR DRIVE SHAFT

Figure 22. RDF and Coal Combination Feeder

placed with an arrangement no. 8 Buffalo Forge high pressure overfire air blower with a 100 hp motor for handling 70°F air as shown in Figure 23.

In addition to replacing the overfire air fan and motor, additional overfire air nozzles were added high and low on both the front and rear boiler walls. The number of 1½ inch air nozzles under the combination feeders, low on the boilers front wall was increased to 20. The nozzles were placed 10 inches on center, across the entire front of the boiler. Eight additional 1-inch nozzles were added to the 8 existing upper and lower nozzles on the rear boiler wall and 8 additional 1-inch nozzles were added to the 8 existing on the upper front boiler wall. The additional upper front and rear nozzles were installed angling down at 30° from the horizontal, while the additional lower front and rear nozzles were installed horizontally.

The total overfire air flow is controlled by an air damper on the discharge side of the high pressure blower. The damper is operated by a Bailey pneumatic control drive and a manual loading station. The pneumatic control drive equipment provides overfire air tracking to the forced draft fan.

The entire overfire air system modification was provided by Detroit Stoker Company of Monroe, Michigan.

AREAS OF SPECIAL DESIGN CONSIDERATIONS AND ALTERNATIVES EVALUATED

Litter and Dust Control

RDF contains appreciable amounts of lint-like, fine fibrous material and pieces of light paper. This material can easily become airborne and settle on building and equipment ledges causing general litter over a wide area if not handled properly.

In order to avoid these problems, several steps were taken in the design and selection of equipment for the RDF storage and feed system. These include:

1. Precompaction and delivery in fully enclosed transfer trailers.
2. RDF unloading and storage indoors.

3. Positioning of the truck access door to permit prevailing wind to blow inward.

4. Use of a simple slider belt conveyor between the RDF fuel storage area and the boiler. Other than a few tracking rollers this conveyor has no moving parts over most of the span between the head and tail pulleys of the conveyor; this limits the amount of maintenance needed over most of the belt span and permits the use of a simple, fully enclosed box for housing for the conveyor.

5. A pneumatic conveying system was also considered but was not used for these reasons:

   a. Space conditions did not permit use of a cyclone,

   b. Pneumatic conveying directly into the furnace is undesirable with a spreader-stoker furnace,

   c. It is generally felt that refuse fed into spreader-stokers should be by gravity and airswept across the grate as close as possible to the grate; this permits maximum burning on the grate, reduces carryover of unburned combustibles and gives better control over combustion air, and

   d. A pneumatic conveying system would also have involved added complexity.

6. Use of a simple and fully enclosed swinging spout feed system at the boiler face reduces the need for equipment access, maintenance, and jams, all of which increase the potential for litter and fugitive dusts.

7. Enclosing the gravity pulley on the conveyor in a heavy duty canvas vacuum cleaner bag type enclosure. This catches and removes most of the carry-back material on the conveyor's return side.

System Controls

In existing plants the boiler control system is designed to control the feed rate of the primary fuel and air flow in response to varying steam demands. An independent and constant RDF system allows the existing fuel control systems to respond to load changes just as it would if the boilers were fired on 100% primary fuels. The refuse feed system conveyor is interlocked to shut down when the overfire air goes down.

In addition to this, all the motors of the RDF feed equipment are interlocked so that any individual piece of RDF feed equipment cannot be operated if the next piece of equipment in the series is not operating. Finally, all RDF feed equipment will shut-down in sequence behind any equipment which might fail during operation.

RDF Feed Control and Continuity of Flow

RDF is fluffy and very light weight, in comparison to other fuels. The density of RDF is about 5-7 lb/cu ft on the feed conveyor. By comparison, the density of coal is 50 lb/cu ft and the density of hog fuel is 20 lb/cu ft.

Because of RDF's tendency to bridge, its heterogenous composition, and its light weight, RDF does not flow smoothly through most feed systems. Control of the flow can be very difficult. A principal design objective, in burning refuse fuel, is to achieve good control over the feed and maintain a smooth continous feed rate.

An auger feed system was selected to provide a metered flow of material. It was felt that an auger feed would work well on the fine RDF available from Madison's Energy Recovery Center. A mechanically adjustable variable speed drive on the augers has ten speed settings and can be used to vary the feed rate from 1-10 tons per hour.

Conveying Between Buildings

As noted earlier, space, added complexity, and boiler type were factors precluding the use of a pneumatic transport line. Since conditions tended to dictate use of a conveyor, the design objectives focused on selection of the simplest conveying system and one which would give maximum control of litter and dust.

The conveying problem involved transport between two buildings at different grades, separated by a series of 4 railroad tracks. The conveyor also had to be positioned in the tight space between the bottom of the coal bin and the boiler front face at a sufficient elevation to permit feed to six boiler feed openings.

Several types of conveyors and conveyor housings were examined. Cleated belt conveyors with heavy duty flexible rubber side walls on simple horizontal rollers were assumed as the standard by which conveyor designs would be evaluated. The housing should provide easy access for maintenance and clean out in all weather conditions while minimizing the opportunity for material spillage. Particular attention in the selection of final engineering design was given to methods of access into the conveyor housing and the ability to prevent fugitive dusts and litter. These requirements lead to selection of the slider belt design, described in previous sections, as the best alternative for the material conveying function.

Flow Splitting at Furnace Wall

Several options were evaluated to provide flow splitting and feed to 6 RDF feed chutes. These are listed and discussed below.

Option 1--

A conveyor feed to a surge bin south of the coal bin with auger outfeed to individual feed chutes was evaluated. This option provided poor location and access to the boiler and access for maintenance. An operating concern for multiple feed from one bin was identified. This, however, is now being done successfully at the Hooker Chemical Niagara Plant.

Option 2--

A conveyor feed to a surge bin either east of the coal bin or south of the boiler firing wall with auger outfeed to either individual feed chutes or small hoppers with augers below was also evaluated. Adequate space was not available for this option and the same operating concern stated above was identified.

Option 3--

A belt conveyor feed to an inline drag conveyor inside the boiler building with feed to six feed openings and return of any overage fraction to the conveyor top side was reviewed. Again, adequate space was not available for this option. The complexity of this system was also identified as a major concern.

Option 4--

Finally, a belt conveyor to a second inline belt conveyor, inside the boiler building, was reviewed. An inline roller type flow splitter above a swinging spout arrangement as illustrated in Figure 20 was designed. This option conformed to the tight space restraints, incorporated a simplicity of design which was desirable and presented no operating concerns.

The final design was fashioned around Option No. 4 but utilized a single RDF feed conveyor. The final design was selected for its simplicity and operating dependability.

Feed into Boiler

Two methods are commonly used to feed prepared refuse fuel into a boiler. The first method is by gravity through distribution chutes with sweep and distribution air at the bottom of the chute for spreading the fuel evenly across the boiler. The second method is by pneumatic conveying with either corner or front wall entry into the boiler. Gravity feed was used at Oscar Mayer and is preferred with spreader-stoker type boilers to maximize burning on the grate and reduce unnecessary entrainment of particulate and carry over of combustibles. Boiler feed chutes should be sloped no more than 30° from vertical to assure gravity flow. Feed chutes must be properly sized, provide adequate drop or slide distance, and have a smooth transition at the bottom to assure good flow into the boiler. The chutes at Oscar Mayer allowed a 9 ft drop prior to entry into the furnace. They are 22 inches by 13-1/2 inches and the bottom transition is smooth with a radius of 1.5 ft. The distribution air must distribute RDF across the full width of the grate and allow for spreading as needed to control bed depth. The sweep air below the RDF helps to reduce friction and aid flow of material into the boiler. While the air flows are an important part of the feed, they must be held to a minimum to allow proper control of overfire and underfire air. Excess air with the feed may increase particulate entrainment and cause cold zones in the boiler which contributes to wall deposits.

Equipment Interlocks

The refuse feed system is independent of the coal feed system. However, a hot boiler with 40% steam load (45,000 lb steam/hr) on coal feed was judged to be necessary prior to starting RDF feed. Another key interlock is between the RDF feed conveyor and the feed augers which shut down when the feed conveyor stops.

Impact on Boiler Operation

An important goal in firing RDF is to minimally affect the coal burning system. The prime concern, when firing RDF, is the ability to control the burning operation. To achieve this, a smooth RDF feed and uniform bed depth are essential. Other areas of concern are overall boiler efficiency, boiler O_2 levels, stack temperature, control of emissions, tube deposits, corrosion, and plugging of gas passages by build-up of soot which reduces furnace draft and impacts on the induced draft fan capacity. The goals in Madison have been to produce and market a relatively high quality refuse fuel with a low ash and moisture content and a 3/4 inch particle size. Such a fuel was used during the tests at Oscar Mayer. This type of fuel burns very well with a heat release faster than coal. None of the concerns noted above posed a severe problem during the course of the demonstration project. The Madison RDF was a good fuel.

RDF FEED SYSTEM ARCHITECTURAL AND DESIGN CONSIDERATIONS

A number of factors were considered in planning and developing the RDF receiving and storage area and RDF feed system. Some of these include architectural and facility layout and design considerations.

Site Location

The RDF receiving and feed facility is shown in Figure 18 and is located on the plant site. The only suitable location for the building was an area across a railroad spur adjacent to the boiler building. The location is roughly in the center of the plant complex and is bounded on the west by the boiler building, the north and east by plant shops and on the south by a manure handling building from the slaughter house. The location has the advantage of good access from the rear delivery gate of the plant off Commercial Avenue and is well buffered from other plant operations. The disadvantages are grade differences, and the presence of four sets of railroad tracks separating the RDF facility and the boiler building. Both have been overcome by selection and installation of a suitable conveying system as discussed earlier in this section.

Traffic

Access to the site is through a single entrance along a drive path. This path does not conflict with other delivery and shipping vehicles and reduces on-site movement to a minimum.

Facility Site Work

The facility site work required was minimal. Since the receiving building uses a concrete slab for storage and does not require pits, except for the small transition pit between the auger bin and the transport conveyor, the site work involved only a slight fill section of the surface immediately under the RDF receiving building. This fill area also provided a sloping surface around the building to direct run off from the building into the existing site drainage system. The transport conveyor is supported at the head end by the boiler structure and in the middle by two A-frame type supports with deep pile footings.

Facility Structure

In order to hold costs to a minimum and conform with other surrounding structures, the RDF receiving building consists of a pre-engineered metal building set on a 7 inch thick concrete slab with 6 ft high reinforced concrete foundation push walls in the area designated for RDF storage. The building is clear span with rolled steel tapered beams and girders and rolled steel "Z" sections for purlins and girders.

Fire Protection

Since the system was used for test purposes only and was generally manned when combustible material was in the building, no fire protection system was installed. If the facility is used on a permanent basis, smoke density alarms with a dry sprinkler system and trumpet type horns or bells would be installed, and ties to the main boiler control room would also be made.

Facility Clean Up, Housekeeping, Dust, and Odor Control

Special attention must be given to good housekeeping practices in the design of any facility where municipal solid waste is handled. The ability to control control fugitive dusts and other light materials along with the control of odor are also important design considerations.

The principal mechanism used in the control of odor from RDF tested at Oscar Mayer is the method of producing the RDF at the City of Madison's Energy Recovery Plant. The processing step which incorporates screening ahead of fine shredding eliminates most of the wet putrescrible material from the fuel. The RDF produced generally has little odor. During the spring and summer months, moisture in the RDF will increase due to grass clippings and other yard waste. A silage smell may be noticeable in the RDF on humid days. Other steps felt to be benefical in the control of odor which were practiced during the test period included:

1. Delivery by enclosed transfer trailers in compacted form.
2. Stockpiling under a roof out of the direct sunlight.
3. Good housekeeping.
4. Storing in a dry area free from rainfall and drainage water.

The material appears to continue to dry during storage. Storage for several days did not appear to contribute to additional odor problems.

Several factors were judged to be important in achieving good environmental control of the RDF storage and feed function for a permanent installation. These factors include:

1. Process design and equipment layout should attempt to minimize material spillage. Equipment transitions and conveyor design are key points at which material spillage can occur.
2. Equipment and building floor supports should be minimized to facilitate floor sweeping with push brooms and mobile sweeping equipment.
3. Groutings around equipment and building support base plates and avoiding ledges around equipment and equipment supports minimizes points where dust and debri can build-up.

4. The area should be served with a centrally located compressed air station and water hose connection. To the extent possible, all areas were RDF spillage occurs away from the storage pile should be swept daily. A long hand-held metal extension attached to a compressed air hose can be used to blow lint and dust off wall and equipment surfaces.
5. Aisles, walkways, restrooms, and other areas frequented by plant personnel should be washed down once a week.
6. Laborers and mobile equipment should be used to sweep up and clean drive areas and transfer spillage points, as necessary, to keep those areas clean.
7. Fully enclosed feed bins and conveying equipment, with a slight negative draft, will be useful in control of fugitive dusts. The dirty air may be cleaned by baghouses or other methods.
8. Plant roof vents can be designed to provide required air changes in areas where personnel are working to maintain a clean air supply.

Equipment Transitions for Smooth Material

Properly designed equipment transitions are essential for smooth material flow and control of the RDF feed system. Areas where special attention must be given include:

1. Feed from slab storage into a feed bin should minimize the distance of material drop to reduce the generation of dust.
2. Feed from a live bottom bin onto belt conveyors must be designed with adequate clearances and baffling to avoid jams and achieve desired material lay-down and distribution on the conveyor for any downstream flow splitting.

3. Dust control hoods must be designed to allow for substantial expansion of RDF without restricting flow.

4. Feed from belt conveyors across flow splitting devices should utilize simple reliable splitting techniques. The important factors here are volumetric area in the zone of transition and the slope and friction characteristics of metal slide surfaces. RDF which is mostly shredded paper is generally in compacted or compressed form in storage and continues to expand at each point of handling or transfer downstream. It has been observed to lay on high friction surfaces below a 60° slope. In some operations low friction plastic with high wear resistant characteristics have been used on the walls of hoppers feeding air locks to improve feed into pneumatic lines.

5. Gravity feed chutes were selected for the test facility. Feed into the chutes was facilitated by a powered splitting roller centered below the head pulley of the RDF transport conveyor and swinging spouts feeding material to chute openings below. The design allowed for a drop of several feet to the splitting roller, a slope of 60° on the walls of the two chutes feeding the swinging spouts, and a near vertical drop in the lower chutes to the points of entry into the boiler. The important transition factors addressed in the system design included the volume of transition area above the splitting roller, depth of splitting roller, size of feed chutes, and feed chute curvature and opening into the boiler.

6. The conveying equipment must be designed for containment and continuous transport of material. The conveyor configuration must prevent material from working free and causing jams and getting between belt surfaces and pulleys which can cause slippage.

Equipment Layout and Access for Maintenance

The equipment layout must allow for easy access by maintenance personnel and mobile equipment and cranes, if necessary, to facilitate the repair or replacement of major equipment items. If possible, heavy equipment should also be near outside walls. The equipment should be accessible through the walls and roof, should major repairs be needed.

SECTION 6

RDF FEED SYSTEM PERFORMANCE AND OPERATION

FEED CHARACTERISTICS OF RDF

To avoid disruption of the City of Madison's commercial operation, which involves production and sale of a finely shredded, low ash RDF to Madison Gas and Electric Company, the normal output of the RDF plant was used as feed for the tests at Oscar Mayer. For this reason the feed material may have been a little easier to handle than if a larger particle size and higher ash content fuel had been used. It is generally believed that a spreader-stoker can efficiently burn a refuse fuel up to 4 inches in particle size and with a higher ash content than presently exists in the Madison RDF [35,36].

Consistency of RDF

The feed material used during the test was a very manageable product composed largely of finely shredded paper, 90% under 3/4 inch. Oversize material was also largely paper in the 3 inch to 4 inch size range. Some oversize material such as textiles, which do not shred easily, can also be found but very little of this type of material was present. The normal moisture range between dry and wet periods, as observed over two years of operation at the process plant, was 20% to 30%. Peaks in moisture and in non-combustible content appear to be effectively removed during the refuse preparation step.

Test No. 21 was conducted using a coarsely shredded refuse fuel, with about 95% of the particles under 4 inches. This material was similar in consistency to the 3/4 inch fuel and proved to be an excellent boiler feed, but contained large pieces of textiles which can cause jams if not handled properly.

Material Flow

The 3/4 inch material flowed smoothly from the auger bin onto the transport conveyor. After a minor adjustment on the auger base plate to carry the material about 1 inch further prior to discharge onto the belt below, the material flowed evenly and uniformly on the belt conveyor and was easily split into two approximately equal streams at the conveyor head pulley, for feed to the swing spouts below. The same was true of the 4-inch RDF during the single test which was conducted with this fuel with the following exception. Some textiles including essentially whole garments, such as a woman's slip, were present in the 4-inch material. Rags and wire quickly bent the flights of the augers at the point of discharge from the feed bin. Because of increased bulk the fuel tended to jam beneath the cover plate over the auger extension past the feed bin wall. These problems were easily corrected by welding metal stiffeners behind the light gage auger flights, and removing the cover plate over 2 ft of auger extension.

A relatively even split of RDF was achieved at the flow splitter, centered above the swinging spouts. Feed to the six air swept chutes was also relatively uniform. With increased operating experience on the 4-inch RDF, operating personnel were able to adjust the sweep and distribution air to achieve uniform spread of material across the boiler grate.

Material Causing Jams

The 3/4 inch RDF used throughout most of the tests showed no tendency to jam except during initial start up when metal flanges were found extending into the feed chutes causing jam points. Also the weight of the RDF was not adequate to open the gravity dampers at the bottom of the combination feeders. The flanges were cut back and the dampers were fixed in an open position when RDF was fired. After these measures were taken no other jams occurred. If the 4-inch RDF is burned on a regular basis, steps may be needed to reduce the top size of materials such as textiles. Some wire was also observed with the 4-inch material. This should not be a problem if the textiles are shredded to a more manageable size. Additional magnetic separation could also be applied if necessary to remove most of the wire.

Dust and Aesthetics

RDF generates dust when it is disturbed or dropped. The RDF tended to generate localized dust as it was pushed into a stock pile or fed into the auger bin. However, fugitive dust was not found to be a problem. The material was easily contained within the storage building and did not generate odors away from the storage area. Near the waste pile a musty odor was sometimes present. No problems related to dust and aesthetics were observed during testing. During the initial tests slippage occurred in the belt conveyor requiring modifications as discussed in Section 5. Some material spillage occurred due to carryback. A removeable canvas cover attached to a dust pan below with metal snaps was placed around the gravity pulley to collect any carryback material. This modification helped provide a clean environment in the boiler room.

Storage

The RDF was easily stockpiled on a concrete slab. The material in the stockpile appeared to retain most of the compaction imparted to the waste during loadout and transport from the process plant. Some heat build-up was noted in material which was stockpiled for three days or more.

RDF FEED SYSTEM OPERATING CHARACTERISTICS

Outfeed

RDF delivered to the test facility was unloaded indoors near the back push wall. Although the storage area was small, a rubber tire front-end loader with an articulate drive was easily able to stockpile the RDF into depths of about 10 feet and shave material off the pile for loading into the feed bin at 90° from the pile.

Feeder

During operation it was found that if material was stacked more than 6 feet above the augers it tended to compact and bridge between the narrow bin walls and produce irregular feed. This could be avoided with a larger bin. With a permanent facility as illustrated in Section 7, the storage and feed function can be simplified by widening the bin and building it slightly below floor level to accomodate loading by both the delivery truck and front end loader. Bins of this type are used at the Madison Gas & Electric Company's Blount Street generating station to burn the City's RDF.

Material Conveying

While all elements of the feed system worked very well after the shakedown period, serious belt slippage problems occurred during start up. The 125 foot long slider belt was initially installed by the manufacturer without a gravity pulley near the head pulley. Friction on the return side was found to be a major problem, and despite numerous steps to overcome the friction, the belt would not run reliably. Some of the corrective steps attempted included:

1. Improved lagging on the head pulley.
2. Belt take up at the tail pulley to obtain maximum tension.
3. Use of powdered lubricants between the belt and conveyor pan.
4. Running for long periods without material on the belt to polish the carriage and reduce friction.

After the installation of the gravity pulley, described in Section 5, the slider belt conveyor has operated reliabily.

Flow Splitting

An adjustable 6-inch diameter powered roller centered below the slider belt head pulley splits the flow into two streams. This is accomodated by a good distribution of material across the slider belt at the point of feed from the auger bin. Each of the two streams then drops to a swinging spout below, which in turn distributes the flow to three feed chutes below. The split of of material into six feed streams is accomplished very smoothly with the system installed.

No significant problems have been encountered with this part of the operation. During start up, fasteners connecting the linkage between the swinging spouts and arms on the spouts were observed to be wearing quickly. The cotter pin fasteners were removed and a sleeve connection was fabricated. This arrangement has performed well.

Feed into Boiler

Material flows by gravity into the boiler, with an air assist at the bottom of the feed chutes. The RDF air swept feed chutes are located immediately above the coal feed and were constructed by the supplier as an intergal part of the feed system. As mentioned earlier, the weight of the RDF from the Madison plant is not adequate to open the balanced damper at the bottom of the chute. This damper must be tied in an open position during RDF feed to avoid jams. The light weight dampers do not seal well when RDF is not being fed and allow some air leakage into the furnace when coal only is being fired. In an effort to seal off any air supply through the RDF feed chutes, when firing coal only, a removable plate has been inserted below the RDF conveyor head pulley and above the splitting roller. Steps are also being taken to seal up minor air leakage points below this level, such as swinging spout arm penetrations and access doors.

The RDF feed chute has a water cooled top plate where it penetrates the furnace wall. During installation the feed chutes were extended too far into the furnace to achieve good insulation around the tip of the water cooled plate. After a period of time this caused calcining of the cooling water and restricted flow through the cooling water section. The tips of the water cooled top plate were cut back and reinsulated and the problem appears to be resolved.

During initial feeding of the RDF, material was observed to mound at several locations in the boiler. This was overcome through operator experience and work with the air sweep adjustments. After the initial start up problems discussed earlier the operation performed smoothly without jams.

RDF FEED SYSTEM PERFORMANCE AND AVAILABILITY

Receiving and Outfeed System

The performance has been excellent except for the minor difficulties noted when burning a 4-inch size RDF and limitations in depth of material in the feed bin. The equipment handled over 600 tons of material during the test period and performed reliably. The availability is estimated to be 97%.

Material Conveying System

After the initial start up difficulties described, the material conveying system has operated very smoothly and with 97% availability.

Flow Splitting System

The performance of this system has been excellent and the performance and availability have been equal to the rest of the feed system.

Combination Feeder

The combination feeders appear to work well. In a new installation the balanced dampers should be replaced with heavy precision machined metal dampers which give tight fittings when RDF is not being burned. The water cooled feeder top plate should be eliminated entirely and replaced with additional refractory.

In order to minimize air infiltration with the RDF feed, a rubber drape was installed a few inches past the conveyor head pulley to achieve a reasonably tight seal above the point where RDF falls across the flow splitter. A rotary seal might also be installed at this point or above the conveyor and ahead of the head pulley.

SECTION 7

ECONOMIC ANALYSIS

1980 CONSTRUCTION COSTS

The modifications to boiler no. 5, the construction of the RDF receiving and feed building, and the acquisition and installation of RDF receiving and feed equipment at Oscar Mayer were done during the first six (6) months of 1980.

Competitively bid contracts were awarded for the construction of the RDF receiving and feed building, the RDF receiving and feed equipment and its installation, and the installation of the overfire air system and combination feeders. The acquisition of the overfire air system and combination feeders was a negotiated contract.

The total 1980 cost of construction for the design, construction and start-up of the RDF receiving and feed facility and boiler modifications was $459,144. Detailed costs are given below.

RDF Receiving and Feed Facility Costs

Building Contracts

General (Including Site Work)	$38,615	
Mechanical	0	
Plumbing	0	
Electrical	9,850	
		$48,465

RDF Receiving And Feed System		
Bin And Auger Discharge System	$26,445	
Conveyor System	70,055	
Six-Way Flow Splitting System	30,916	
RDF Receiving and Feed System Installation	44,716	
Miscellaneous Equipment	9,804	
		$181,936
Other RDF System Cost		
Engineering Consultants	$27,688	
City Engineering Staff (October 1, 1978 to January 25, 1980 and April 19, 1980 to July 14, 1980)	23,134	
Start-Up Costs (Estimated)	15,000	
		$65,822
Building And Equipment Capital Cost		$296,223
Boiler No. 5 Modifications		
Boiler Modifications		
Combination Feeders	$54,875	
Overfire Air System	22,822	
Erection Cost	43,004	
Erection Supervision	11,100	
Controls	1,200	
		$133,001
Other Boiler Costs		
Engineering Consultants	$8,500	
City Engineering Staff (January 26, 1980 to July 13, 1980)	6,420	
Start-Up Costs (Estimated)	15,000	
		$29,920
Boiler Capital Cost		$162,921

The grand total, for the 1980 acquisition of RDF receiving and feed equipment, the construction of the RDF receiving and feed building and the modification of Boiler No. 5 was $459,144.

PROJECTED CAPITAL AND OPERATING COSTS FOR A PERMANENT INSTALLATION AT OSCAR MAYER

Projected 1981 Capital Costs

The RDF receiving and feed system, installed at Oscar Mayer, has served as a simple and reliable pilot facility over the test period. The system can easily be expanded for permanent operation. A proposed layout for a fully-operational permanent facility is shown in Figure 24. Most of the test facility including the receiving building, RDF transport conveyor and boiler feed equipment in the boiler room can be used in a permanent installation. The auger bin used during the tests should be replaced with a heavier duty bin of larger capacity to accommodate direct unloading by a 75-cubic yard transfer trailer and provide greater automation. The building can be expanded to accommodate this change as shown in Figure 24. The projected 1981 Capital Cost for a fully operational long-term facility are as follows:

RDF Receiving and Feed Facility Costs		
Building Contracts		
General (Including Site Work)	$90,000	
Mechanical	10,000	
Plumbing	10,000	
Electrical	18,000	
		$128,000
RDF Receiving and Feed System		
Bin and Auger Discharge System	125,000	
Auger Discharge Conveyor	26,000	
Conveyor System	87,000	

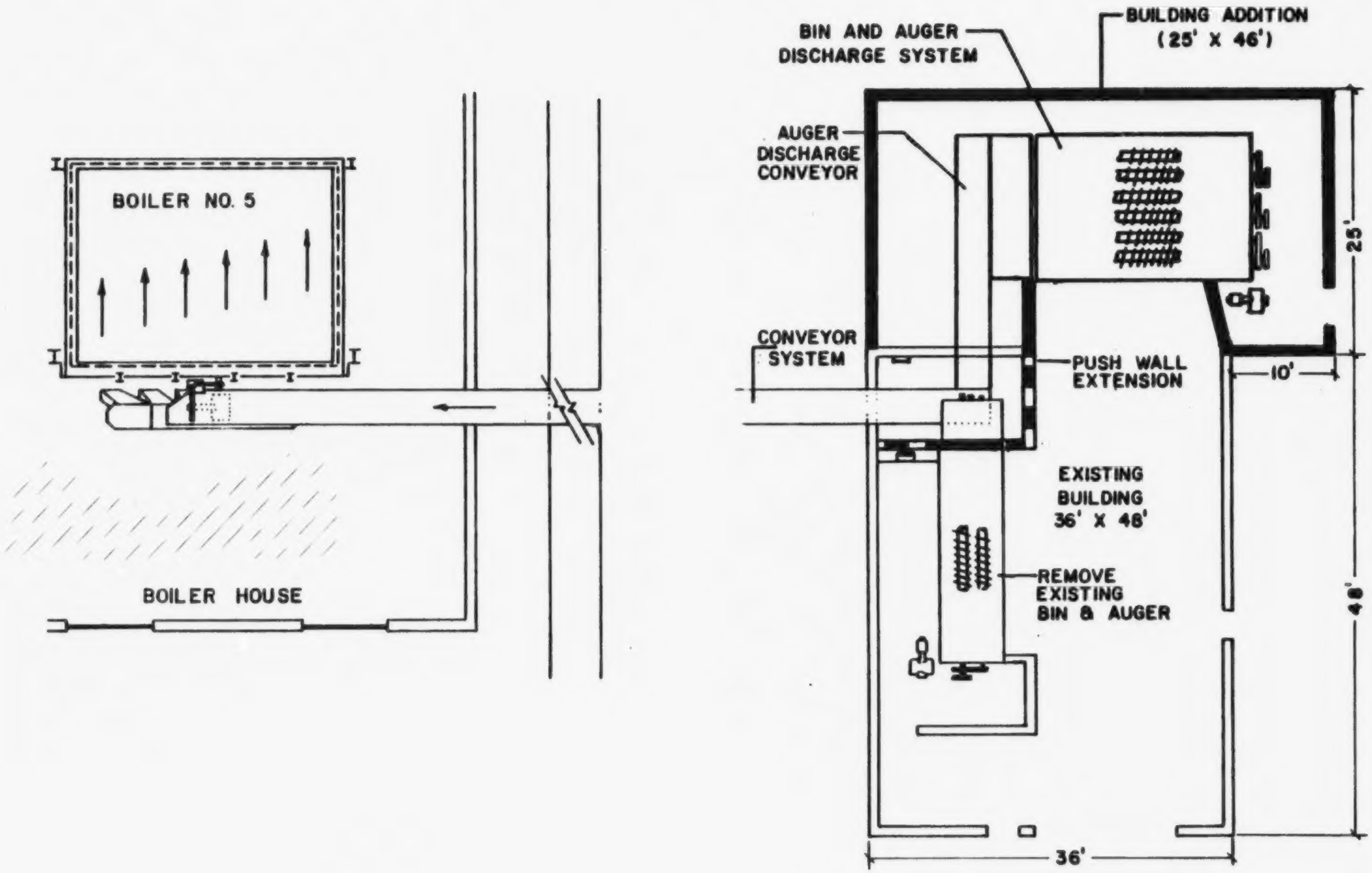
BIN AND AUGER DISCHARGE SYSTEM
BUILDING ADDITION (25' X 46')
AUGER DISCHARGE CONVEYOR
CONVEYOR SYSTEM
PUSH WALL EXTENSION
25'
10'
48'
36'
EXISTING BUILDING 36' X 48'
REMOVE EXISTING BIN & AUGER
BOILER NO. 5
BOILER HOUSE

Figure 24. Proposed RDF Receiving and Feed Facility Additions

Six-Way Flow Splitting System	39,000	
Rubber Tired Front End Loader	42,000	
RDF Receiving and Feed System Installation	66,000	
Miscellaneous Equipment	21,000	
		$406,000
Total Construction Costs		$534,000
Other Costs		
Engineering and Supplemental Services - 10% of Construction Cost	53,000	
Contingencies - 10% of Construction Cost	53,000	
Start Up Costs and Miscellaneous - 10% of Construction Costs	53,000	
		$159,000
Total Capital Cost		$693,000
Annual Cost (12% for 10 years)		116,000
Capital Cost Saved by Existing Facilities		296,000
Net Capital Cost (Total Capital Cost - Capital Cost Saved)		397,000
Net Annual Cost (12% for 10 years)		70,260

The projected costs are based on actual 1979 Construction Costs escalated 1% per month to September of 1981, and manufacturer's cost data.

Projected Annual Operating Costs for the RDF Receiving and Feed System

The projected economics for a permanent RDF Receiving and Feed System at Oscar Mayer are reviewed below.

The receiving facility shown in Figure 24 can store two 75-cubic yard transfer trailer loads of RDF or about 30 tons. About two-thirds of this tonnage can be loaded directly into the large heavy-duty live bottom auger bin. The bin will hold 3 to 4 hrs of feed material and will greatly reduce operator attention over that experienced during the testing. The test bin required reloading every 15 to 20 minutes. During a normal operating day, the boiler is operated over a ten to twelve hour period at 90,000 lb steam/hr to meet plant demands.

During the tests, refuse fuel up to 48% of heat load, was fired without a problem. At a steam load of 90,000 lb steam/hr, this will require about 8 tons/hr of RDF feed. The feed system up to the point of entry into the boiler can handle 8 tons/hr.

The operating costs at Oscar Mayer are projected assuming a RDF firing rate of 5 tons/hr for 10 to 12 hrs/day, 5 days per week for an annual RDF utilization of 12,500 to 15,000 tons. The projected annual operating costs for utilizing RDF are as follows:

Annual Operating Costs

Labor (Operation and Maintenance)		$30,000
Annual Spare Parts		20,000
Utilities		12,000
Equipment Replacement		10,000
Increased Ash Disposal		8,000
Administration		5,000
Miscellaneous		5,000
Projected Annual Operating Costs		$90,000
Cost/ton of RDF at 12,500 tons/yr	$7.20	
at 15,000 tons/yr	$6.00	

The Oscar Mayer and Company R.D.F. Market

An expanded market for RDF would greatly impact on Madison's Resource Recovery Program. Estimates have shown that the development of a second market, at Oscar Mayer could represent the utilization of an additional 12,500 - 15,000 tons of RDF annually.

This assumes that approximately 5 tons per hour of RDF would be burned for a minimum of 10 hrs/day and possibly up to 12 hours per day. To meet this additional fuel demand, the production of RDF at the Madison Area Resource Recovery Center, would require an increase of 40% to 50%. The design of the Madison Area Resource Recovery Center anticipated the development of additional RDF markets and is capable of processing 50% more municipal solid waste with no additional capital cost required. Given that no additional capital investment would be required for a production increase of 50% and that 56% of the total operating cost at the Madison Area Resource Recovery Center is fixed, a second market could reduce the City's unit price for RDF production by as much as 28%.

Present production levels process all the residential municipal solid waste collected by the City of Madison's Division of Streets and Sanitation, therefore, the raw waste for a production increase would have to come from a source other than City collections. Procurring the additional raw waste does not present a problem. Private waste collectors have expressed an interest in participating in the program as have several small neighboring communities. Waste collectors, other than the City of Madison, discharging at the Madison Area Resource Recovery Center, would be charged a per-ton tipping fee. This new source of revenue would be applied against the Recovery Center's operating costs and provide a reduction in the unit price for RDF production in addition to the 28% mentioned above. The conditions for developing a RDF market with Oscar Mayer appear favorable.

Fuel Value of RDF

The price paid for RDF will vary depending on the structure of the agreement between the RDF producer and the fuel user. The value of RDF as a supplemental fuel can be established by comparing costs to the user to produce process steam or power with and without supplemental RDF. The value of RDF may be obtained by assuming equivalent fuel costs per unit heat output less any increased incremental capital and operating costs when using RDF. The heating value of the RDF is typically less than coal. The boiler efficiency is generally reduced when RDF is burned. These factors reduce the dollar value of RDF per ton compared to coal. In Appendix D a general equation is developed relating these factors. The result is

$$P_{RDF} = 0.90\ P_{coal}\ (HV_{RDF}/HV_{coal}) - K,$$

where

P = price of fuel per ton

HV = as received higher heating value of fuel

K = incremental increase in capital and operating costs per ton associated with co-firing RDF

REFERENCES

1. Boley, G.L., and M.L. Smith. Development and Implementation of a Resource and Energy Recovery Program for the City of Madison, Wisconsin. In: Proceedings Second International Conference and Trade Exhibition Materials and Energy from Refuse, Berlin, West Germany, 1979. 195 pp.

2. Barlow, K.M., G.L. Boley, and M.L. Smith. Design, Evaluation and Operating Experience of the City Of Madison - Madison Gas and Electric Company Energy Recovery Project. In: Proceedings ASME National Waste Processing Conference, Washington D.C. 1980. 414 pp.

3. Hennessey, E.M. Request for Proposal No. CI-77-0226, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977. 8 pp.

4. Geissler, S.B. Development of Procedures for Characterization of Refuse Derived Fuel. Independent Study Report. Department of Civil and Environmental Engineering, University of Wisconsin-Madison, 1980.

5. American Society for Testing and Materials. Draft Procedures for Analysis of Refuse Derived Fuel, 1979

6. Riibe, S.M. Test Firing Refuse-Derived Fuel in an Industrial Stoker-Fired Boiler. M.S. Thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Wisconsin, July, 1981.

7. American Society for Testing and Materials. 1980 Annual Book of ASTM Standards. Part 26, Gaseous Fuels; Coal and Coke; Atmospheric Analysis. Philadelphia, Pennsylvania, 1980.

8. Winegartner, E.C., et al. Coal Fouling and Slagging Parameters. The American Society of Mechanical Engineers, 1974.

9. Degler, G.H., H.G. Rigo and B.T. Riley. A Field Test Using Coal: RDF Blends in Spreader-Stoker-Fired Boilers, EPA-600/2-80-096, August 1980.

10. Federal Register. Environmental Protection Agency Standards of Performance for New Stationary Sources, Vol. 42, No. 160, August 18, 1977.

11. Methodology for the Determination of HCl Emissions for Stationary Sources. U.S. EPA preliminary report, Research Triangle Park, N.C., 1977.

12. Rollins, R. and Homolya, J.B. Measurement of Gaseous Hydrogen Chloride Emissions from Municipal Refuse Energy Recovery Systems, Env. Sci. Tech., Vol. 13, No. 11, 1979. 1380 pp.

13. Lentzen, D.E., et al. IERL-RTP Procedures Manual: Level 1 Environmental Assessment (2nd Edition). U.S. Environmental Protection Agency, EPA-600/7-78-201, October 1978.

14. Maraval, P. Emissions Tests from a Stoker Fired Boiler Using Coal and RDF. M.S. Thesis, University of Wisconsin-Madison, 1980.

15. The American Society of Mechanical Engineers. Steam Generating Units. Power Test Code. ASME PTC 4.1, New York, 1974

16. Niessen, W.R. Properties of Waste Materials. In: Handbook of Solid Waste Management. D.G. Wilson et al. Van Nostrand Reinhold Company, New York, 1977. 10-62 pp.

17. Van Meter, D., et al. Evaluation of the Ames Solid Waste Recovery System Part II - Performance of the Stoker Fired Steam Generators. EPA-600/7-79-229, October 1979.

18. Greenberg, R.R., W.H. Zoller, and G.E. Gordon. Composition and Size Distribution of Particles Released in Refuse Incineration. Environmental Science & Technology. Vol. 12, May 1978. 566-573 pp.

19. U.S. Environmental Protection Agency. Quality Criteria for Water. Washington, D.C., July 1976.

20. U.S. Environmental Protection Agency. Hazardous Waste Management Systems Part III: Identification and Listing of Hazardous Waste. Federal Register, May 1980. 33084-33136 pp.

21. Kaakinen, J.W., et al. Trace Element Behavior in Coal-Fired Power Plant. Environmental Science & Technology, Vol. 9, September 1975. 862-869 pp.

22. Petersdorf, R.J. Co-firing Coal and RDF in a Utility Steam Generator, Operational Experience and Corrosion Probe Evaluation. In: Proceedings of the American Power Conference, Chicago, Illinois, 1980.

23. Olexsey, R.A. Estimated Ground Level Concentrations of Pollutants from Waste to Energy Plants. In: Proceedings of the ASME Waste Processing Conference, Washington, D.C., 1980.

24. Joensen, A.W. Retrofitting Boiler Plants for RDF Operation. In: Proceeding of the Utilizing Municipal Solid Waste as a Fuel Conference, Madison, Wisconsin, 1980.

25. Joensen, A.W., et al. RDF Power Plant Operating Experience. Presented at the Utilizing Municipal Solid Waste as a Fuel Conference, Madison, Wisconsin, 1980.

26. Vaughan, D.A., et al. Summary Report on Environmental Effects of Utilizing Solid Waste as a Supplementary Power Plant Fuel. EPA R804008-02-2, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1978.

27. Wilson, M.E., et al. Engineering and Economic Analysis of Waste to Energy Systems. EPA68-02-2101, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

28. Rochford, R.S., et al. Considerations in the Design of a Shredded Municipal Refuse Burning and Heat Recovery System. In: Proceedings of the ASME Waste Processing Conference, Chicago, Illinois, 1978.

29. Smith, M.L. M.L. Smith Environmental Trip Reports, 1974-1978.

30. Dehchik, M., D.I. Cramblete, et al. Akron Recycle Energy System is on the Line. In: Proceedings of the ASME Waste Processing Conference, Washington, D.C., 1980.

31. Hileman, G.P., and F.B. Pyle. Recycle Energy for Central Heating and Process Steam. In: Proceedings of the International District Heating Association, Chicago, Illinois, 1977.

32. Hall, J.L., et al. Environmental Emissions from a Suspension Fired Boiler while Burning RDF and Coal Mixtures. In: Proceedings of the ASME Waste Processing Conference, Washington, D.C., 1980.

33. MRI Report. St. Louis Demonstration Project Final Report: Power Plant Equipment, Facilities, and Environmental Evaluations. EPA 68-02-1871, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977.

34. Klumb, D.F. Issues for RDF as Applied to Utility Boilers. In: Proceedings of the Prepared Fuels and Resource Recovery Technology Conference, Nashville. Tennessee, 1981.

35. Deboe, H.M., and R.C. Lutwen. Burning Municipal or Plant Refuse with Coal as a Support or Main Fuel. In: Proceeding of the Industrial Coal Conference, Lexington, Kentucky, 1978.

36. Pollock, W.H. Generating Steam from Refuse in Industrial Boilers. In: Proceeding of the International District Heating Association Conference, Dixiville, New Hampshire, 1979.

APPENDIX A

EQUATIONS FOR STACK SAMPLING

Nomenclature:

A_{nozzle}: Area of nozzle (in^2)

BW: percent moisture by volume

C_{HCl}: concentration of HCl in stack gas (dry basis)

C_{H_2O}: water constant (1/.94 = 1.064)

C_{orif}: orifice coefficient

C_p: constant (=1)

C_s: pitot calibration number (=.81)

C_{SO_2}: concentration of SO_2 in stack gas (dry basis)

C_{stack}: stack coefficient

C_T: stack temperature divided by meter temperature

C_{TE}: concentration of trace element in stack gas (dry basis)

D_S: diameter of stack (=7.5ft)

E: emissions rate per 10^6 Btu input

EA: excess air

HL: heat input rate (10^6 Btu/hr)

K: iso-kinetic constant

MW: molecular weight

N: normality

P_m: barometric pressure (in Hg)

P_o: constant pressure (=29.92 in Hg)

$PM_{loading}$: particulate emissions (gr/wscf)

Q: flow rate through stack (cfm)

Q_{ave}: average flow rate (=.75 cfm for a stack sampler)

Q_s: standard wet flow rate through stack (wscfm)

T_m: dry gas meter temperature (R)

T_o: constant temperature (=528 R)

T_s: stack temperature (R)

v_{nozzle}: gas velocity in nozzle (ft/min)

v_{stack}: gas velocity in stack (ft/min)

$\bar{v}_{stack}$: average gas velocity in stack (ft/min)

V_m: volume of gas through gas meter (ft^3)

$V_{m\ std}$: dry volume of gas through gas meter (standard conditions)

V_T: volume of titrant (ml)

V_{wc}: water condensed (in water impingers and silica gel)

ΔP_{nozzle}: velocity pressure in nozzle (in H_2O)

$\overline{\Delta P}_{nozzle}$: average velocity pressure in nozzle (in H_2O)

ΔP_{orif}: velocity pressure in orifice (in H_2O)

ΔV: volume of gas through gas meter between two readings (ft^3)

ϕ: nozzle diameter (in)

Calculations:

1. Iso-kinetic Equation:

$$\Delta P_{orif} = K \Delta P_{nozzle}$$

$$K = (953.4\ C_{stack} C_s A_{nozzle})^2 / (C_{orif} C_{H_2O} C_p C_T)^2$$

with

$$C_{stack} = (T_s/P_m)^{1/2}$$

$$C_{orif} = .1313(T_m/P_m)^{1/2}$$

$$C_T = T_s/T_m$$

$\Delta P_{orif} = (Q_{ave}/C_{orif})^2$ (by definition for a stack sampler)

We finally obtain:

$$A_{nozzle} = (Q_{ave}C_{H_2O}C_T)/(953.4\ C_{stack}C_s(\overline{\Delta P}_{nozzle})^{1/2})$$

$$= (\pi/4)\,\phi^2$$

So we pick the ϕ value which gives us the closest area.

2. Moisture Determination:

$$BW = V_{wc}/(V_{wc}+V_{m\ std})$$

$$V_{m\ std} = 17.64\ V_mP_m/T_m = V_mT_oP_m/(T_mP_o)$$

3. Molecular Weight Determination:

$$MW = .32\ \%O_2 + .44\ \%CO_2 + .28\ (\%CO + \%N_2)$$

4. Velocity Determination:

$$v_{stack} = 85.45\ C_s\ (T_s\overline{\Delta p}_{nozzle}/P_mMW)^{1/2}$$

$$v_{nozzle} = (\Delta VT_s)\ /\ (2A_{nozzle}T_m(1-BW_m))$$

The iso-kinetic assumption $v_{stack} = v_{nozzle}$ can then be checked

5. Flow Rate Determination:

$$Q = \bar{v}_{stack}\ (\pi/4)D_s^2$$

$$Q_s = Q(T_o/T_s)(P_m/P_o)$$

6. Excess Air Determination:

$$EA = ((\%O_2-.5\ \%CO)/(.264\ \%N_2-\%O_2 + .5\ \%CO)) \times 100$$

7. Particulate Emissions Determination

$PM_{loading}$ = ((Filter Weight + Probe and Cyclone Wash Weight) x 15.432) $/(V_{wc}+V_{m\ std})$ (gr/wscf)

$$E_{PM} = 0.00857\ Q_s\ PM_{loading}/HL\ (lb/10^6\ Btu)$$

8. SO_2, HCl and Trace Element Emissions:

$$C_{SO_2} = 3.53 \times 10^{-4}\ N\ V_T/V_{m\ std} \quad \text{(lbm/dscf)}$$

or

$$C'_{SO_2} = 2163\ N\ V_T/V_{m\ std} \quad \text{(ppm)}$$

$$E_{SO_2} = 60\ Q_s(1\text{-}BW)\ C_{SO}/HL \quad \text{(lb/}10^6\text{ Btu)}$$

$$C_{HCl} = 7.85 \times 10^{-4}\ N\ V_T/V_{m\ std} \quad \text{(lbm/dscf)}$$

or

$$C'_{HCl} = 8444\ N\ V_T/V_{mstd} \quad \text{(ppm)}$$

$$E_{HCl} = 60\ Q\ (1\text{-}BW)\ C_{HCL}/HL \quad \text{(lbm/}10^6\text{ Btu)}$$

$$C_{TE} = \text{(grams TE/grams sample) (lbm sample)}/V_{m\ std} \quad \text{(lbm/dscf)}$$

$$E_{TE} = 60\ Q_s(1\text{-}BW)\ C_{TE}/HL \quad \text{(lbm/}10^6\text{ Btu)}$$